Radioecology: Nuclear Energy and the Environment

Volume II

Authors

F. Ward Whicker, Ph.D.
Professor
Department of Radiology and
Radiation Biology
Colorado State University
Fort Collins, Colorado

Vincent Schultz, Ph.D.
Professor
Department of Zoology
Washington State University
Pullman, Washington

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PREFACE

These volumes attempt to address many of the complex questions of nuclear energy and the environment. It is intended as a broad survey of the field of radiation ecology, with in-depth coverage of selected topics. The rationale, scope, and social relevance of the field, as well as a brief historical review, are treated in the introductory chapter. Volume I, Chapters 2 and 3, covering ecological and radiological principles as they relate to radiation ecology, are included for readers who may need such a background for enhanced understanding of subsequent chapters. Environmental radioactivity, both natural and man generated, is covered in some depth from the standpoint of sources and environmental distribution in Volume I, Chapter 4. Volume I, Chapter 5 on radionuclide movement in ecosystems is offered with respect to individual radionuclides and observations in selected land and water environments. A reasonably detailed treatment of mathematical models and their use in predicting rates of movement and degree of concentration in ecosystem components is presented in Volume II, Chapter 1 with emphasis on linear, first-order kinetics of single and multicompartment systems. Comprehension of the material presented in this chapter is not a requirement for understanding other chapters in this book. Volume II, Chapter 2 is a survey of knowledge on the effects of ionizing radiation on individual organisms, natural populations, and communities of terrestrial and aquatic environments and is presented in order that in Volume II, Chapter 3 the implications of radioactivity in the environment from nuclear activities of man can be more fully explored.

Within the appendix (Volume II) we have included a detailed citation of the major books and bibliographies on radiation ecology, a table of radionuclides and their physical characteristics, and a list of review articles on specific radionuclides as related to the environment.

In order that the reader may more completely explore the literature we have followed each chapter with suggested additional readings. Many of these publications and others cited within the text are governmental releases and rather difficult to locate. To facilitate their procurement we have included references to abstract sources, for example *Nuclear Science Abstracts,* when we thought it would be helpful. Publications of the U.S. Department of Energy (DOE) and its predecessors, Atomic Energy Commission (AEC) and Energy Research and Development Administration (ERDA) are available in many depository libraries throughout the U.S. and in some foreign countries. Within these depositories one can also find selected foreign publications.

Although scientists are likely to be the major readers, we believe that administrators, managers, and laymen can find some relevant reading herein. These volumes represent the impressions gained by the authors over two decades of research and teaching of the subject on radiation ecology.

Radiation ecology deals with natural and man-produced radioactivity, the movement of such materials in the environment, and the effects of ionizing radiation on populations and biotic communities. It is not a science unto itself; rather it is a hybrid that contains elements of several basic physical and biological disciplines. However, it has been found to be extremely relevant in the practical sense to a society that wants both more energy and a quality environment and to some of the more esoteric aspects of basic science as well. From a rather practical beginning which was concerned with the environmental implications of the first nuclear detonations, radiation ecology has enlarged its scope to the myriad questions raised in regard to nuclear power reactors and the associated fuel cycle and other potential means of gaining energy from nuclear technology. In addition, techniques utilizing radionuclides have contributed to many disciplines within the environmental sciences.

Some 10 years ago, the authors began writing a textbook on radiation ecology and

attempted to write a complete, authoritative and accurate book, incorporating most of the pertinent literature. That was our mistake...we never finished the book. It became a full-time task merely to catalogue the stream of new papers, let alone to read and assimilate them. Therefore, our resolve in these volumes is to tell it as we see and understand it, utilizing only a small proportion of the reference material available, and realizing that our knowledge is incomplete and subject to error. In this effort we have primarily utilized those papers with which we have had personal contact. Knowingly, we have not included many excellent papers, particularly from the foreign literature. However, we have attempted to rectify this shortcoming by including many of these papers in the additional readings following each chapter.

We are indebted to a very long list of colleagues, students, friends, and family, each of whom contributed in some important way to the preparation of this volume. We are particularly indebted to our wives and students who provided much encouragement and inspiration to finish these volumes. We specifically acknowledge Susan L. White and Patricia L. Schultz for accomplishing the tremendous task of typing several manuscript drafts and April D. Whicker for artwork and proofreading. Finally, we are grateful to Dr. Allyn H. Seymour, friend and colleague, who contributed useful suggestions on the final manuscript, and to Janelle Sparks of CRC Press for her patience and guidance during the publication process.

F. Ward Whicker
Fort Collins, Colo.

Vincent Schultz
Pullman, Wash.

THE AUTHORS

F. Ward Whicker, Ph.D., is a Professor in the Department of Radiology and Radiation Biology at Colorado State University, Fort Collins. He teaches and conducts research in radioecology and allied subjects.

Dr. Whicker received a B.S. degree in applied chemistry in 1962 and a Ph.D. degree in radiation biology in 1965 from Colorado State University. In 1965, he received training in the use of radioisotopes in ecological research at the University of Hannover in West Germany. His academic and research history includes visiting professorships at the Institute of Arctic Biology, University of Alaska, Fairbanks, and the Department of Botany, University of North Carolina, Chapel Hill.

Dr. Whicker is a Fellow of the American Association for the Advancement of Science and currently holds membership in the Ecological Society of America, the Wildlife Society, Health Physics Society, and the Society of Sigma Xi. He also belongs to several academic honor societies including Phi Kappa Phi, Kappa Mu Epsilon, and Beta Beta Beta.

Dr. Whicker has published approximately 60 journal articles dealing with various topics in radioecology and basic biology. He has authored several review articles and book chapters on radioecology and has prepared over 40 technical reports on various research contracts and consultantships.

The research activities of Dr. Whicker have included studies on the behavior of radionuclides in aquatic and terrestrial ecosystems, the effects of radiation on natural populations, environmental impacts of energy technologies, radionuclide transport modeling and dose assessment, and description and analysis of natural ecosystems. He has served as an advisor to governmental agencies and industrial firms on problems of nuclear waste disposal, uranium production, nuclear gas stimulation, and assessment of environmental radioactivity.

Vincent Schultz, Ph.D., is Professor of Zoology and Wildlife Biology, Washington State University, Pullman, and a member of the Graduate Faculty of the Program in Environmental Science. Dr. Schultz graduated in 1946 from Ohio State University, Columbus with a B.Sc. degree in agriculture and obtained a M.Sc. degree in zoology in 1948 and a Ph.D. degree in zoology from the same university. In 1954, he was granted an M.Sc. in statistics by Virginia Polytechnic Institute, Blacksburg. In addition, he attended the University of Connecticut, Storrs, Yale University, New Haven, Conn., and the University of Pennsylvania, Philadephia under the Army Specialized Training Program, completing the premedical program in 1945. Following his graduation from Virginia Polytechnic Institute he was for 2 years a U.S. Public Health Service Fellow in biostatistics at The Johns Hopkins University, Baltimore, Md. During the period 1959 to 1966, he was employed as an ecologist by the U.S. Atomic Energy Commission, Washington, D.C., in which he was involved in developing a program in radiation ecology under the supervision of the late Dr. John N. Wolfe. Since that time he has been associated with Washington State University teaching courses in mathematical, statistical, and radiation ecology. Dr. Schultz has served as a consultant to the U.S. Department of Energy and its predecessors, the U.S. Nuclear Regulatory Commission, Battelle Pacific Northwest Laboratories, and Sandia Laboratories. He has presented invited lectures on aspects of radiation ecology and has published over 100 manuscripts on a variety of subjects.

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Dedicated
to
April D. Whicker
Patricia L. Schultz
and
our children and students

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RADIOECOLOGY: NUCLEAR ENERGY AND THE ENVIRONMENT

F. Ward Whicker and Vincent Schultz

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Volume II

Chapter 1

QUANTITATIVE ASPECTS OF RADIONUCLIDE TRANSPORT

I. INTRODUCTION

The ability to predict is a critical test of understanding. This chapter provides an extension of the qualitative description of radionuclide transport in Volume I, Chapter 5 to a quantitative representation of several of the more important transport processes. Such quantitative representation is extremely useful for organization and understanding of the subject and also for the prediction of radionuclide burdens in biological tissues resulting from environmental releases. The passage and implementation of the National Environmental Policy Act of 1969 (NEPA) has resulted in the requirement of government agencies and industry to state the environmental consequences of radionuclide releases prior to permitting actions which would lead to such releases. Compliance with this requirement necessitates the use of models which are used to predict the transport of radionuclides within ecosystems and the resulting radiation doses to critical biological tissues.

Development and use of transport models requires conceptual understanding and mathematical formulation of physical, chemical, and biological processes which effect radionuclide movement in the environment. It also requires the synthesis of any number of process formulations to enable prediction of inventories of radionuclides in ecosystem components of interest. Such ecosystem components as soil, plants, animals, etc. are normally treated as compartments of a system. Compartment systems in which the individual pools are linked by flow processes are subject to mathematical description. The complexity of mathematical formulation increases rapidly with the number of compartments and intercompartmental flows. Also, the computational methods can in practice vary with the complexity of the system.

This chapter is intended as an introduction to some of the commonly used methods of quantitatively predicting radionuclide transport. It is organized with a section on individual transport processes, one on the kinetics of compartment systems, and a final section on general comments relative to the development and use of transport models. An extremely large number of methods of varied complexity have been used to describe transport of radionuclides. The authors are able to touch upon but a few of them, and in many cases, in a superficial, pragmatic way. The authors introduce a significant body of literature which will need to be consulted for most serious modeling efforts. An understanding of the material in this chapter should enable the reader to begin some independent modeling of simple systems and to communicate with experts on more complex systems or in special cases, such as those where critical decisions might depend upon the accuracy of a model.

II. TRANSPORT PROCESSES

A radionuclide transport process refers to any natural phenomenon which results in the movement of material from one place to another, or from one media to another. A process may be purely physical, chemical, or biological in nature or it may result from some combination of physical, chemical, or biological mechanisms. Some transport processes of generally major importance are described below.

A. Dispersion

1. Atmospheric

The subject of atmospheric dispersion has been of increasing importance largely

because of the ever-growing problem of air pollution. Atmospheric dispersion refers to the spreading out of particles or gases from a source, which normally results in a decreasing concentration of particles or gases with distance from the source. The process of atmospheric dispersion results from a combination of natural phenomena, including large-scale physical displacement of the surrounding air mass, turbulent diffusion, and molecular diffusion. Molecular diffusion is normally a minor factor in dispersion. The nature and motions of the atmosphere have a dominating effect on the behavior of gases or aerosol particles, and therefore, the subject of meteorology is a basic foundation for the prediction of atmospheric dispersion.[1-3]

The fundamental cause of the normally rapid dispersion of gases or very small particles in the atmosphere is turbulence, the irregular, chaotic motion that is characteristic of most natural flows of gases or liquids. This process is normally orders of magnitude more important than molecular diffusion in effecting dispersion. Turbulence is easy to recognize if one simply watches a sensitive wind vane for a period of time. Except for calm periods, a wind vane undergoes continuous fluctuations which vary in magnitude, frequency, and mean direction. Turbulence is three-dimensional in that it can be broken into three directional components.

Theories of turbulent diffusion exist and these are useful for fundamental understanding of atmospheric processes and their effects. However, the practical application of diffusion theory to dispersion problems is unwieldy. Fortunately, simpler formulations have been developed which are relatively easy to apply to practical problems. These generally embody the normal or "Gaussian" distribution function, which not only provides a fundamental solution to the Fickian diffusion equation, but also satisfactorily simulates most real data. Such formulations are frequently referred to as "Gaussian plume models". The authors shall now present some of the simpler versions of these and discuss their use. The methodology is based largely on guides prepared by Turner[4] and Smith.[5] These guides in turn were developed on the basis of earlier works.[6-9]

A three-dimensional coordinate system is important to have in mind prior to the presentation of dispersion equations (Figure 1). Distance downwind of a point source is the x coordinate, the perpendicular distance from the plume centerline or x axis is the y coordinate, and the z coordinate represents the height aboveground, or the distance above the xy plane. The height of the plume centerline is referred to as H, which is the sum of the source height h and any plume rise, Δh.

The concentration, X, of gases or aerosol particles having negligible settling velocities (generally particles < 20 μm diameter) at coordinates x, y, and z from a continuous point source is given by

$$X(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z\bar{u}} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\} \quad (1)$$

This equation assumes that the plume is reflected from the ground surface, i.e., there is no deposition at the surface. The problem of deposition will be considered later. In Equation 1, X(x,y,z) is air concentration at coordinates x,y, and z in $\mu Ci/m^3$, Q = source strength in μCi/sec, u = mean wind speed at height H in m/sec, σ_y = horizontal dispersion coefficient at coordinate x in m, σ_z = vertical dispersion coefficient at coordinate x in m, and H = effective plume height in m = source height + plume rise.

Before discussing these parameters and their determination for application to spe-

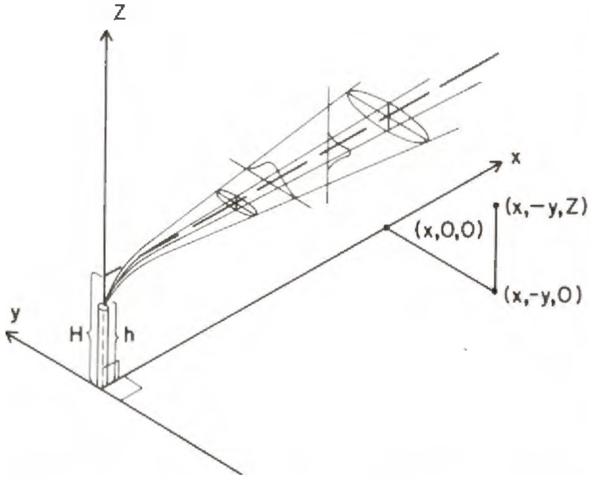

FIGURE 1. Coordinate system for atmospheric dispersion calculations.

cific problems, the authors shall present some simplified forms of Equation 1. In most cases, we are concerned with ground-level air concentrations along the plume centerline, i.e., where z and y = 0. For a ground-level air concentration, Equation 1 reduces to

$$X(x,y,0) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \quad (2)$$

For a ground-level air concentration along the plume centerline, y and z = 0,

$$X(x,0,0) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \quad (3)$$

Finally, for a ground-level point source with no effective plume rise, H = 0,

$$X(x,0,0;\ H = 0) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \quad (4)$$

In order to apply the preceding equations to real problems, one must determine the appropriate parameter values. This is not always simple, because these values vary with meteorological conditions and with the nature of the source term.

The parameter $\bar{u}$ represents the mean wind speed acting on the plume and for most purposes can be taken as the mean wind speed at height H. If instruments are located at H, then instrument readings can be averaged over the time domain of concern and applied in the appropriate dispersion equation. If, however, instrument readings are made at some height other than H, then a correction must be applied. The earth's surface exerts a drag or friction force on the wind, which results in a shearing stress that varies with height. This results in a wind speed profile which can be estimated roughly from[5]

$$\bar{u}_H = \bar{u}_1 \left(\frac{H}{z_1}\right)^p \quad (5)$$

Table 1
PASQUILL STABILITY CATEGORIES IN RELATION TO WIND SPEED AND SOLAR RADIATION

	Daytime insolation			Nighttime conditions	
Surface wind speed (m/sec)	Strong	Moderate	Slight	Thin overcast or ≥ 4/8 cloudiness[a]	Thin overcast or ≤ 3/8 cloudiness
<2	A	A—B	B		
2	A—B	B	C	E	F
4	B	B—C	C	D	E
6	C	C—D	D	D	D
>6	C	D	D	D	D

Note: A — extremely unstable conditions; B — moderately unstable conditions; C — slightly unstable conditions; D — neutral conditions (applicable to heavy overcast, day or night); E — slightly stable conditions; and F — moderately stable conditions.

[a] The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon which is covered by clouds.

From Turner, D. B., Workbook of Atmospheric Dispersion Estimates (revised 1970), Rep. AP-26, Office of Air Programs, U.S. Environmental Protection Agency, Research Triangle Park, N.C., 1971.

where $\bar{u}_H$ = mean wind speed at height H, $\bar{u}_1$ = measured wind speed at height z_1, and p varies from 0.5 for stable conditions to 0.25 for unstable conditions. The value of p varies with atmospheric stability, which is basically determined by the temperature profile. As a general rule, one can consider the atmosphere to be "stable" during nighttime inversions and "unstable" during the daytime. If the atmosphere is considered "neutral", one should also use a value for p of 0.25. The atmosphere is considered neutral whenever overcast conditions prevail and during certain other conditions (Table 1).

The parameters σ_y and σ_z are termed the "dispersion coefficients" for the y and z coordinates, respectively. They represent the standard deviations of contaminant concentrations through the center of a plume in the horizontal or vertical planes (Figure 1), and therefore, are a measure of the degree of plume spreading. The dispersion coefficients are functions of downwind distance (x) and atmospheric stability (Figures 2 and 3). Note that x, downwind distance, is manifest in Equations 1 to 4 through its effect on σ_y and σ_z.

As mentioned previously, atmospheric stability is largely determined by the vertical temperature profile of the atmosphere. Atmospheric stability refers to the tendency of the air column to resist or enhance vertical motion. In very general terms, when the air temperature decreases with altitude, there is a tendency for warm air near the surface to rise because it has a lower density than the colder air above it. Conversely, during an inversion, the air temperature may rise with altitude and there is little or no tendency for vertical motion. The first case leads to instability, whereas the second encourages stability. This concept however, is somewhat oversimplified, for several recognizable and distinctive temperature profiles exist.[5] These are usually gauged against the "dry adiabatic lapse rate" which is approximately −1°C/100 m.

In practice, one seldom has measurements of air temperature vs. altitude and thus a more practical scheme of determining atmospheric stability has been developed.[8,9] Such a scheme employs wind speed and incoming solar radiation to determine stability

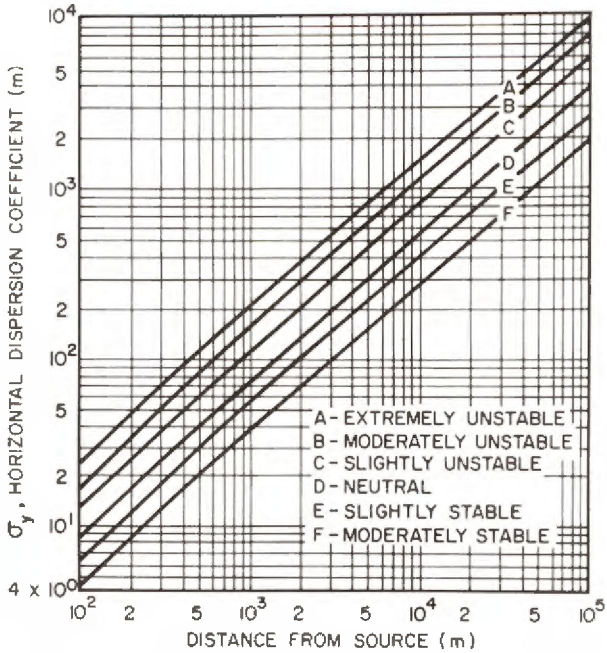

FIGURE 2. Horizontal dispersion coefficient vs. downwind distance by Pasquill stability categories.[4]

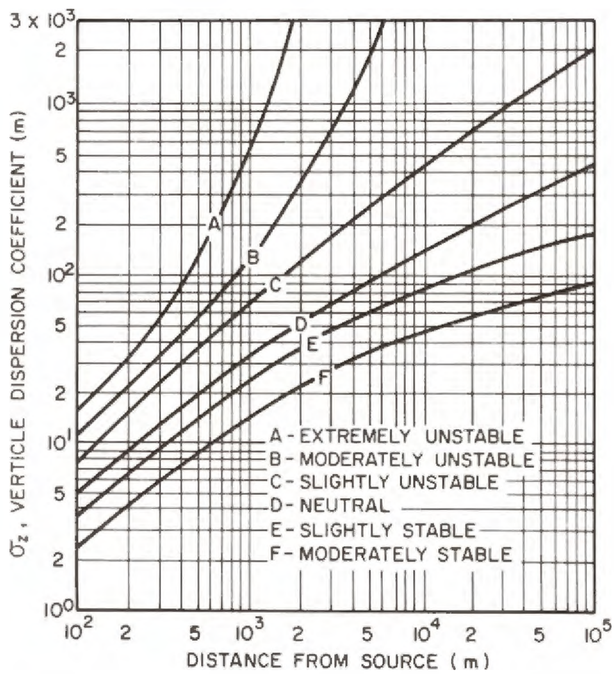

FIGURE 3. Vertical dispersion coefficient vs. downwind distance by Pasquill stability categories.[4]

classes (Table 1). These stability classes, often referred to as "Pasquill stability categories", are then used to determine the appropriate dispersion coefficients in Figures 2 and 3. Note that the dispersion coefficients increase as the air column becomes less stable, which effectively lowers the air concentration of an airborne substance. Table 1 reflects the fact that atmospheric dispersion is generally enhanced during the daytime hours of strongest incoming solar radiation and inhibited during the calm, nighttime hours. If a heavy overcase is present, the neutral condition (D) is assumed, whether day or night.

The effective plume height H is the sum of the physical stack height or release point and the plume rise. The plume rise, which results mainly from its exit velocity and bouyancy (if warmer than the ambient temperature), is affected by several parameters and is a complex subject in its own right. Numerous equations for estimating plume rise under various conditions have been used.[2,4,5] A semiempirical equation developed by Holland[10] is commonly used

$$\Delta h = \frac{vd}{\bar{u}}\left[1.5 + 2.68 \times 10^{-3}\, p\left(\frac{T_s - T_a}{T_s}\right) d\right] \tag{6}$$

where v = stack gas exit velocity (m/sec), d = inside diameter of stack (m), $\bar{u}$ = mean wind speed (m/sec), p = atmospheric pressure (mb), T_s = stack gas temperature (K), and T_a = ambient temperature (K). To account for the effects of atmospheric stability, it is recommended that Δh in Equation 6 be increased by 10 to 20% for unstable conditions and decreased by 10 to 20% for stable conditions. The effective plume height H has a major effect on air concentrations near the source and on the distance at which maximum concentrations can be expected. As H increases, the air concentrations near the source decrease and the distance where maximum concentrations occur increases.[4]

A special situation arises when a stable air layer exists above an unstable layer. This condition, often referred to as an "elevated inversion", prevents aerosol generated in the unstable layer from diffusing into the elevated stable layer. The interface between these air layers is often termed a "lid". Since the "lid" effectively limits vertical diffusion, ground-level air concentrations do not diminish as rapidly with distance as they would without the inversion lid. Turner[4] presents the following equation for calculation of air concentrations when an inversion lid is present:

$$X(x,y,z) = \frac{Q}{\sqrt{2\pi}\,\sigma_y\, L\, \bar{u}} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \tag{7}$$

where L is the height of the inversion lid in m. This equation is applicable for any distance $x > 2\,x_L$; x_L being the distance where $\sigma_z = 0.47$ L. For $x < 2\,x_L$, Equation 1 is applicable. Equation 7 assumes that x is independent of z, for any z between 0 and L, and that $H < L$.

The atmospheric dispersion equations presented thusfar are short-term; i.e., they are valid only over a period of time during which meteorological conditions remain reasonably constant. Ordinarily, such periods last only a few hours. The next problem, therefore, is that of determining longer-term average air concentrations at a given point. Obviously, solutions to long-term average calculations must account for changes in wind speed and direction over time, as well as changes in atmospheric stability. A useful formula for estimating long-term average air concentrations has been developed,[2]

$$\bar{X}(x,0,0) = \sqrt{\frac{2}{\pi}} \left[\frac{f\bar{Q}}{\bar{\sigma}_z \, \bar{u} \left(\frac{2\pi x}{n} \right)} \right] \exp \left[-\frac{1}{2} \left(\frac{H}{\bar{\sigma}_z} \right)^2 \right] \tag{8}$$

where $\bar{X}$ (x,0,0) = long-term average ground-level air concentration at distance x in $\mu Ci/m^3$, $\bar{Q}$ = average source strength in $\mu Ci/sec$, f = fraction of time that wind blows in wind rose sector of interest, having a width of $2\pi x/n$ m, n = number of sectors in wind rose used to determine f and $\bar{u}$, $\bar{\sigma}_z$ = average vertical dispersion coefficient, based upon the average stability class, and $\bar{u}$ = average wind speed for the wind rose sector of interest. Wind rose data in the vicinity of the source is an obvious necessity for this calculation. A wind rose is a polar diagram which shows wind direction frequency and speed frequency by direction (Figure 4). It is usually based upon actual records of wind speed and direction obtained at a nearby location over some extended period of time, and thus is a reasonable predictor of wind patterns.

For prediction of seasonal or annual averages of air concentrations, $\bar{\sigma}_z$ is difficult to estimate because the term will be affected by stability class. However, if the frequency with which each stability class occurs is known, then the average air concentration may be estimated by [4]

$$\bar{X}(x,0,0) = \sum_s \sum_N \left\{ \sqrt{\frac{2}{\pi}} \left[\frac{f(s)\, f(N)\, f\, \bar{Q}}{\sigma_z(s)\, \bar{u}(N) \left(\frac{2\pi x}{n} \right)} \right] \exp \left[-\frac{1}{2} \left(\frac{H(N)}{\sigma_z(s)} \right)^2 \right] \right\} \tag{9}$$

where f(s) = frequency of stability class s, f(N) = frequency of wind speed class N, f = frequency that wind blows in sector of interest, $\bar{\sigma}_z(s)$ = vertical dispersion coefficient for stability class s, $\bar{u}(N)$ = representative wind speed for wind speed class N, and H(N) = effective plume height for wind speed class N. Usually, the most difficult data to obtain for use in Equation 9 are the frequencies of the various stability classes. If site-specific data are not available, reasonable estimates based upon solar azimuth tables may be obtained from the literature.[4,11,12]

To this point the discussion of atmospheric dispersion is relevant only to those cases where the airborne pollutant does not attach to surfaces at or near ground level. As a rule, many gases will exhibit such behavior, i.e., they do not become significantly depleted from the plume by interacting with the surface. On the other hand, particulates and some gases tend to adhere to surfaces such as vegetation, soil, buildings, water, etc. when they are in the proximity of such surfaces.[13] This effectively removes material from the plume and the process is termed "cloud depletion". Cloud depletion may occur as a result of precipitation or through dry depositional phenomena. The subject of cloud depletion is sufficiently complex that we shall not attempt a simplified treatment here. However, if certain types of information are available, formulas and nomograms exist for making the necessary calculations.[2,13] For dry deposition, wind speed, and a term called the "deposition velocity" (to be defined in the section on deposition) are the necessary parameters. Parameters termed "rainout" and "washout" coefficients are needed for cloud depletion estimates when precipitation is the dominant mechanism. These will also be discussed in the section on Deposition.

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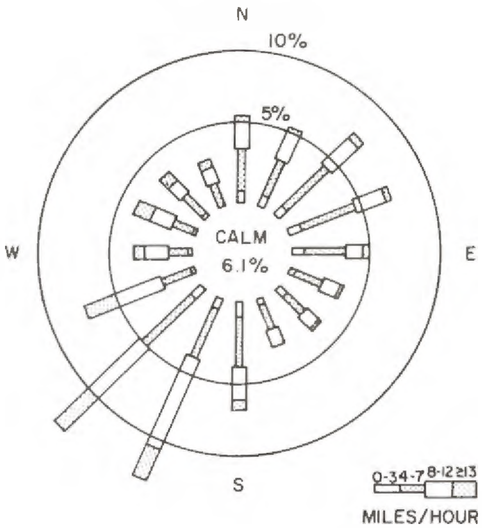

FIGURE 4. A 16-sector windrose for the month of July, based upon 10 years of data in Cincinnati. The position of each "spoke" indicates wind direction; the length of each spoke indicates the frequency of that direction, and the length of each segment indicates wind speed frequency.

The equations presented in this section are also limited to point sources. In practice, however, nonpoint sources are frequently encountered. For example, the source configuration may be considered as an area. A large number of point sources in close proximity may be treated as an area. Another example might be carbon monoxide emanating from a city. Another common source configuration is a line, such as a highway. A practical treatment of these cases is provided by Turner.[4]

The case of an instantaneous source has also not been presented. An example of an instantaneous source would be an explosion or "puff" of material. In this situation the puff will diffuse in three dimensions so that the cloud will increase in size, but decrease in mean air concentration as it travels in a trajectory determined by wind direction. The air concentration at some point downwind of the source is a time function, with maximum values occurring when the cloud is centered over the point. The following formula may be used to estimate ground-level air concentrations downwind from an instantaneous source:[4]

$$X(x,y,0) = \frac{2\,Q_T}{(2\pi)^{3/2}\,\sigma_x'\,\sigma_y'\,\sigma_z'} \exp\left[-\frac{1}{2}\left(\frac{x-\bar{u}t}{\sigma_x'}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z'}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y'}\right)^2\right] \quad (9a)$$

where Q_T = total quantity of material released, σ_x', σ_y', σ_z' = standard deviations of concentration distributions through the puff in the downwind, crosswind, and vertical directions in m,* $\bar{u}$ = mean wind speed in m/sec, and t = time in sec after the release.

* These parameters are not the same as the dispersion coefficients used for continuous source calculations.

Table 2
PREDICTIVE EQUATIONS FOR σ_y' and σ_z' FOR THE RANGE BETWEEN 100 AND 4000 M

Parameter (m)	Stability	Approximate power function (X in m)
σ_y'	Unstable	$0.14X^{0.92}$
	Neutral	$0.06X^{0.92}$
	Very stable	$0.02X^{0.89}$
σ_z'	Unstable	$0.53X^{0.71}$
	Neutral	$0.15X^{0.70}$
	Very stable	$0.05X^{0.61}$

Data from Slade, D. H., Ed., Meteorology and Atomic Energy 1968, U.S. AEC Rep. TID-24190, U.S. Atomic Energy Commission, Washington, D.C., 1968.

The quantities σ_y' and σ_z' can be estimated from power functions of distance (Table 2). Less is known about diffusion in the downwind direction, and therefore, good estimates of σ_x' are apparently not available. In general, however, one should expect the values of σ_x' to be about the same as σ_y'.[4]

2. Hydrospheric

Dispersion of radioactive substances released to aqueous environments may be considerably more difficult to describe than atmospheric dispersion. Aqueous dispersion is analogous to atmospheric dispersion in that turbulent mixing is a dominant mechanism. However, the turbulent characteristics of most natural bodies of water are subject to a large number of variables which change dramatically in time and space and thus elude accurate prediction. Therefore, a completely generalized approach to calculation of aqueous dispersion is not available.

Factors which affect dispersion of radionuclides in water include water depth, motion, temperature profile, configuration, wind, tides, ground water influences, and other features of the aquatic environment. Each body of water has unique mixing characteristics and these vary in time and from place to place. Further complication arises from interactions of radionuclides with solid surfaces, such as suspended materials, bottom sediments, and aquatic biota. Such interactions include sorption, which varies with radionuclides and their physicochemical forms, and with the abundance, proximity, and nature of the solid surfaces. Sorption phenomena effectively remove, to some extent, most radionuclides from the liquid phase, thereby altering subsequent movement. For example, in a river a radionuclide may attach strongly to suspended debris, which may settle to the bottom in a quiet pool, only to be resuspended later by high water flow and carried to some undetermined location downstream. Extending the complexity even further, a multitude of possible chemical interactions may lead to precipitation or desorption of radionuclides.[14]

Although a completely generalized approach to the calculation of aqueous dispersion does not exist, numerous models which have certain requirements and limitations are available. An excellent summary of these has been prepared by Gloyna et al.[15] In addition, the U.S. Nuclear Regulatory Commission[16] has described some fairly practical methods for solving advection-diffusion equations for several example-types of waters such as nontidal rivers, open coasts, estuaries, and impoundments. The models presented or cited in these documents require various data on the hydrology of the system of interest, diffusion coefficients, and source terms. Finding the appropriate

parameter values for a given system may not be easy, and in many cases, research with dyes or other tracers may be required to obtain the appropriate parameter estimates. In addition, most of the models do not have simple analytical solutions so numerical solutions by computer are often required. The complexity and diversity of the more realistic aqueous dispersion models discourages us from attempting a treatment of them in this volume. Instead, we shall present a few very simple dilution equations that might be appropriate for crude approximations when certain simplifying assumptions can be made. Furthermore, our discussion will be limited to smaller streams and impoundments in which nearly complete mixing can be assumed to occur rapidly.

In the case of a chronic discharge to a small, turbulent stream, the mean cross-sectional concentration of a pollutant immediately downstream of the discharge point may be estimated by

$$\bar{C}_s = \frac{R_d}{F_s + F_d} \tag{10}$$

where $\bar{C}_s$ = mean cross-sectional concentration in stream ($\mu Ci/m^3$), R_d = rate of discharge ($\mu Ci/sec$), F_s = flow rate of stream (m^3/sec) at point of discharge, and F_d = flow rate of discharge (m^3/sec). In this case, R_d is the product of $\bar{C}_d$, the mean concentration in the discharge ($\mu Ci/m^3$) and F_d. The flow rate of a stream may be estimated at the point of discharge by direct physical measurements from

$$F_s = y\,\bar{z}\,\bar{u} \tag{11}$$

where y = stream width (m), $\bar{z}$ = mean depth (m), and $\bar{u}$ = mean velocity (m/sec). Therefore, one can estimate $\bar{C}_s$ by

$$\bar{C}_s = \frac{\bar{C}_d F_d}{y\,\bar{z}\,\bar{u} + F_d} \tag{12}$$

The value of $\bar{C}_s$ would in practice represent the mean value of numerous concentrations measured along the cross section of the stream immediately downstream of a discharge point. It is assumed here that the concentrations would be uniform with depth. The uniformity of the C_s values measured at a given point downstream would depend upon the geometry of the discharge and turbulence at the point of discharge. The value of $\bar{C}_s$ at some distance downstream (x), uncorrected for removal processes, could be estimated from

$$\bar{C}_s(x) = \frac{\bar{C}_d F_d}{y\,\bar{z}\,\bar{u} + F_d + F' - E} \tag{13}$$

where $C_s(x)$ = mean uncorrected cross-sectional concentration at x distance downstream ($\mu Ci/m^3$), F' = flow rate contributed by any tributary streams or runoff between x = 0 and x (m^3/sec), and E = evaporation loss (m^3/sec) between x = 0 and x.

To correct $\bar{C}_s(x)$ for processes such as adsorption, sedimentation, or biological uptake, one may write

$$\bar{C}_s'(x) = \bar{C}_s(x)\,e^{-kx} \tag{14}$$

where $\bar{C}_s'(x)$ = mean cross-sectional concentration at x meters downstream, corrected for removal processes ($\mu Ci/m^3$), and k = removal coefficient (m^{-1}). In practice, k is the fraction of activity removed per meter and its numerical value would need to be

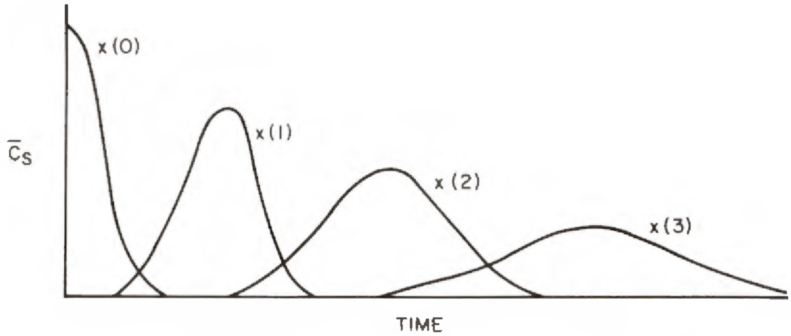

FIGURE 5. Time plot of mean cross-sectional concentrations ($\bar{C}_s$) of a radionuclide at various points downstream (x) following an acute point of discharge in a stream.

determined empirically or theoretically. In a real situation, it is possible that k would vary over distance due to changes in stream geometry, sediment characteristics, and biological activity.

To correct water concentrations for removal processes as well as radioactive decay, one may add an additional term

$$\bar{C}_s'(x) = \bar{C}_s(x)\, e^{-kx} e^{-\lambda\left(\frac{x}{\bar{u}}\right)}$$
$$= \bar{C}_s(x)\, e^{-\left(k + \frac{\lambda}{\bar{u}}\right) x} \qquad (15)$$

where λ = radioactive decay constant in sec^{-1}, λ = ln 2/half-life (sec) and $\bar{u}$ = mean stream velocity over the distance x = x/mean transit time (sec).

In the case of an acute, point discharge of radioactivity to a stream, the material will be carried downstream by the flow (advection) and as the material moves downstream, it will spread out at a rate determined by the degree of turbulence. This will form a "patch" which will become larger with downstream distance; however, the peak concentration will diminish with distance (Figure 5). The calculation of values of $\bar{C}_s(x,t)$ would require advanced methodologies and appropriate diffusion parameters.

Let us next consider the simple case of a lake or reservoir that is sufficiently small to permit nearly complete mixing during the residence time of radionuclides which enter the impoundment. Assuming that the impoundment has a steady flow through it (i.e., an inlet and outlet) and that the mixing volume is constant, one may develop simplified equations to estimate the mean concentration of a radionuclide, assuming a chronic, steady input. For the cases where it may be assumed that the radionuclide mixes rapidly in the water phase and does not decay or interact with sediments or biota during its residence in the lake,

$$\frac{dq}{dt} = R_d - q\left(\frac{F}{V}\right) \qquad (16)$$

where q = the total inventory of radionuclide in the lake (μCi), R_d = the rate of radionuclide discharge to the lake (μCi/sec), V = mixing volume of the lake (m^3), F = flow of water out of the lake (m^3/sec), and F = V/τ, where τ is the mean residence time (sec) of a parcel of water in the lake. When the lake is in equilibrium with respect to the radionuclide, dq/dt = 0,

$$R_d = q\left(\frac{F}{V}\right)$$

and

$$q = \frac{R_d V}{F}$$

Then the mean radionuclide concentration in the lake at equilibrium ($\overline{C}$) in $\mu Ci/m^3$ is

$$\overline{C} = \frac{q}{V} = \frac{R_d}{F} \qquad (17)$$

The radionuclide ^3H (tritium) could be expected to exhibit this behavior quite well since it is an excellent tracer for hydrogen, and if in the chemical form of HTO it would trace the behavior of water and negligible interactions with sediments and biota would be expected. Most other radionuclides, however, could be expected to reach diminished equilibrium concentrations in the water because of adsorption, sedimentation and uptake, and perhaps also because of radioactive decay. In order to correct for these effects, one may write

$$\begin{aligned} \frac{dq}{dt} &= R_d - q\left(\frac{F}{V}\right) - qk - q\lambda \\ &= R_d - \left(\frac{F}{V} + k + \lambda\right) q \qquad (18) \end{aligned}$$

where k = a net rate constant, indicating the fraction of q in the water phase which is removed by adsorption, sedimentation, and uptake processes per second, and λ = radioactive decay constant in sec^{-1} and λ = ln 2/half-life (sec). For the equilibrium situation, one then has

$$R_d = \left(\frac{F}{V} + k + \lambda\right) q$$

and

$$\overline{C}' = \frac{q}{V} = \frac{R_d}{F + kV + \lambda V} \qquad (19)$$

where $\overline{C}'$ = mean concentration in $\mu Ci/m^3$, corrected for radioactive decay, as well as adsorption and uptake processes. The value of k could be expected to vary over a wide range, depending on the radionuclide, its chemical form, and the nature of the biota and sediments. In practice, k could be determined experimentally. The values of F and V can be estimated from physical measurements.

The case of an acute discharge to a small impoundment can also be handled rather simply, providing that initial mixing occurs rapidly with respect to τ, the mean residence time of a parcel of water. In this case,

$$\overline{C}'(t) = \frac{q(t)}{V} = \frac{q(0)}{V} e^{-\left(\frac{F}{V} + k + \lambda\right) t} \qquad (20)$$

where $\overline{C}'$ (t) = the mean time-dependent corrected concentration ($\mu Ci/m^3$), q(t) = the time-dependent radionuclide inventory (μCi), q(0) = the initial inventory (μCi) = the total amount discharged to the lake, and t = time (sec).

It is again emphasized that the preceding equations account for maximum possible dilution and some basic physical and biological processes which remove radioactive material from the water phase. They do not consider turbulent diffusion processes;

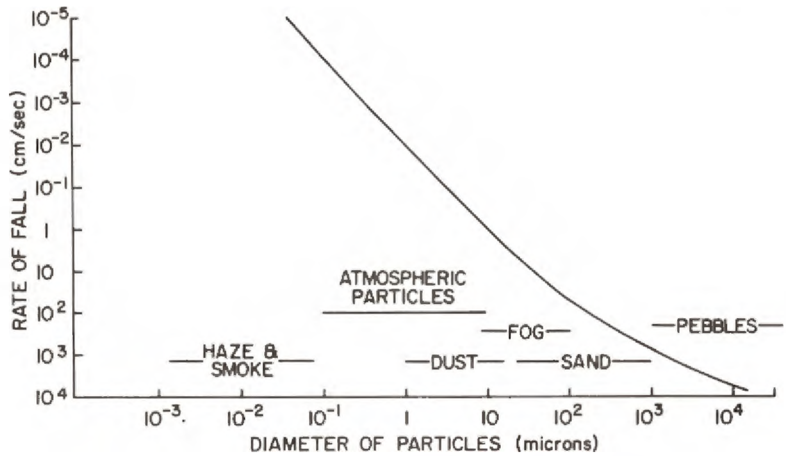

FIGURE 6. Relative size and approximate rate of fall of familiar particles. (Adapted from Bagnold, R. A., *The Physics of Blown Sand and Desert Dunes*, William Morrow, New York, 1942. With permission.)

rather it is assumed that mixing proceeds rapidly with depth and width in the case of streams, and throughout the physical mixing volume in the case of lakes or other small impoundments. This assumption cannot ordinarily be made for larger bodies of water, and two- or three-dimensional dispersion models should therefore be employed for such systems.[15-17] Regardless of the specific model used to predict aqueous concentrations resulting from radionuclide release to a water body, the appropriate parameters should be determined on a site-specific basis, and then the model should be validated with real data if it is to achieve a reasonable degree of credibility.

B. Deposition

Deposition calculations are necessary for a number of practical calculations in which one must estimate the input of radionuclides from the atmosphere to aquatic or terrestrial ecosystems. In addition, it is sometimes necessary to correct atmospheric dispersion estimates for cloud depletion caused by deposition.

In the following discussion, the authors shall consider the deposition of particulate and gaseous matter from the atmosphere to the ground surface. The types of deposition to be considered include gravitational settling of larger particles (generally > 20 μm in diameter) and deposition of smaller particles and gases. The deposition of smaller particles and gases largely unaffected by gravitational settling, occurs through dry deposition phenomena and precipitation. A brief treatment of each form will be provided.

As with other processes which have been described in quantitative terms, the authors have attempted to treat depositional processes in the simplest and most practical manner possible. In doing this, the authors have largely ignored the true complexity of the subject. Therefore, the methods presented may be most useful for general understanding and some order-of-magnitude estimates. Most critical calculations should be performed by experts who are familiar with the latest advances in the field.[2,13,18]

The scope of the problem of deposition can be placed in general perspective by consideration of the physical dimensions of particles and their approximate rates of fall. Bagnold[19] prepared a diagram which shows the general size to rate of fall relationship for various aerosols with which we are familiar (Figure 6). Particles having rates of fall of the order of 1 cm/sec or less will normally be affected by air turbulence much more than by gravity. As a result, particles small enough to have such low fall

Basic data for the R-Q relation

R	Ca	Q	R	Ca	Q
1	24	24	2×10^3	0.41	1.64×10^6
2	16	64	4×10^3	0.40	6.40×10^6
4	8.8	140	6×10^3	0.40	1.44×10^7
6	6.4	230	1×10^4	0.41	4.10×10^7
10	4.2	420	2×10^4	0.44	1.76×10^8
20	2.9	1.16×10^3	4×10^4	0.46	7.33×10^8
40	1.8	2.88×10^3	6×10^4	0.46	1.65×10^9
60	1.5	5.40×10^3	1×10^5	0.44	4.40×10^9
100	1.2	1.20×10^4	2×10^5	0.41	1.64×10^{10}
200	0.80	3.20×10^4	3×10^5	0.20	1.80×10^{10}
400	0.61	9.76×10^4	4×10^5	0.09	1.44×10^{10}
600	0.54	1.94×10^5	6×10^5	0.10	3.60×10^{10}
1×10^3	0.46	4.60×10^5	1×10^6	0.14	1.40×10^{11}

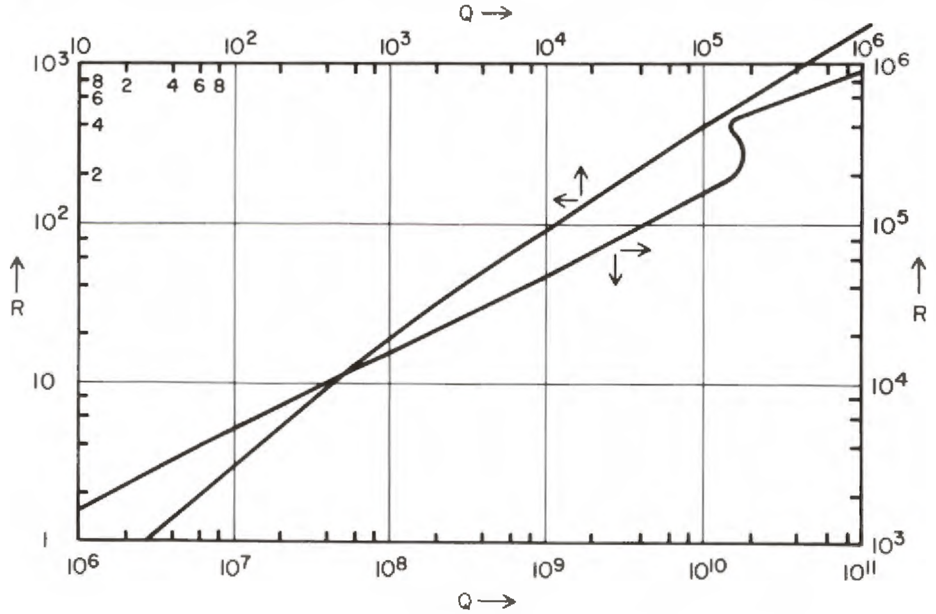

FIGURE 7. The R-Q relation for R values ≥ 1. Arrows indicate scales to be used with each section of the R-Q curve. (After McDonald, J. E., *J. Meterol.*, 17(4), 463, 1960. With permission.)

rates may remain airborne for extended periods of time and travel great distances. Consequently, their rates of deposition cannot normally be predicted on the basis of gravitational settling.

1. Gravitational Settling

In general, the deposition of particles having diameters greater than about 20 μm and densities greater than 1.0 g/cm³ may be predicted on the basis of gravitational settling. Of principal importance is the fall velocity of such particles. When a particle is allowed to fall through the air (or any other fluid medium), its velocity will increase, at first with the acceleration of gravity, but thereafter, at a decreasing rate of acceleration until it reaches a constant velocity called the "terminal velocity". The decreasing acceleration is the result of the force of resistance offered by the fluid medium, which acts in opposition to the weight of the particle. The radius and density of the particle determine its weight and downward force, while the opposing force, sometimes called the aerodynamic drag force, is determined by the size of the particle, its velocity, the density and viscosity of the air medium, and its resistance to sheer stress. The terminal

Table 3
VALUES OF ν AND Q/W FOR SELECTED ALTITUDES IN THE I.C.A.O. STANDARD ATMOSPHERE

Z (km)	ν (cm²/sec)	Q/W (sec²/gm cm)	Z (km)	ν (cm²/sec)	Q/W (sec²/gm cm)
0	1.46×10^{-1}	9.53×10^{4}	30	8.40	2.02×10^{3}
2	1.72×10^{-1}	8.59×10^{4}	40	4.13×10^{1}	3.71×10^{2}
4	2.03×10^{-1}	7.57×10^{4}	50	1.63×10^{2}	8.87×10^{1}
6	2.42×10^{-1}	6.61×10^{4}	60	4.69×10^{2}	3.31×10^{1}
8	2.91×10^{-1}	5.73×10^{4}	70	1.43×10^{3}	1.23×10^{1}
10	3.53×10^{-1}	4.95×10^{4}	80	6.05×10^{3}	3.21×10^{0}
15	7.30×10^{-1}	2.45×10^{4}	90	3.28×10^{4}	5.90×10^{-1}
20	1.60×10^{-1}	1.12×10^{4}	100	1.91×10^{5}	9.81×10^{-2}
25	3.50	5.13×10^{3}			

After McDonald, J. E., *J. Meteorol.*, 17(4), 463, 1960. With permission.

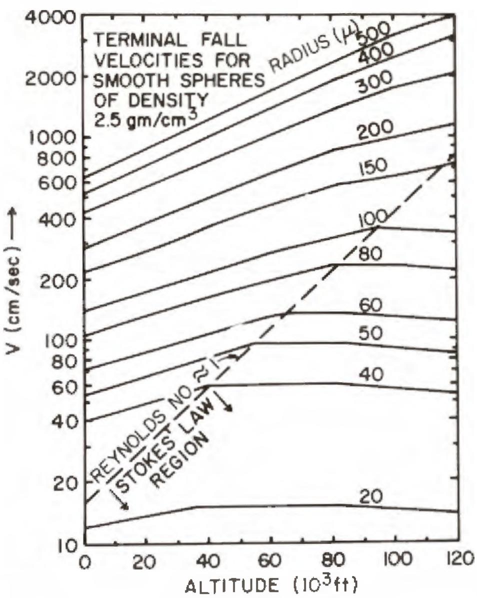

FIGURE 8. Terminal fall velocity (V) for smooth spheres of density 2.5 g/cm³ as a function of altitude in the I.C.A.O. Standard Atmosphere. (After McDonald, J. E., *J. Meteorol.*, 17(3), 380, 1960. With permission.)

velocity V_g is achieved when the opposing forces are equal, and for smooth spheres

$$\frac{1}{2} \rho_m V_g^2 C_d \pi r^2 = \frac{4}{3} \pi r^3 \rho_s g \tag{21}$$

where ρ_m = density of the fluid medium (g/cm³), V_g = terminal fall velocity (cm/sec), C_d = drag coefficient (dimensionless), r = particle radius (cm), ρ_s = particle density (g/cm³), and g = gravitational acceleration constant (981 cm/sec²). Solving Equation 21 for the terminal velocity gives

$$V_g^2 = \frac{8 \rho_s g r}{[illegible]} \tag{22}$$

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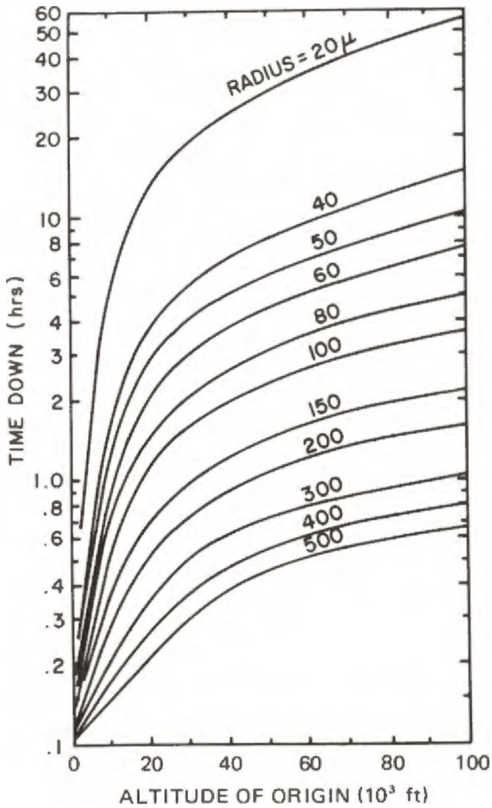

FIGURE 9. Times of descent of smooth spheres of density 2.5 g/cm³ originating at various altitudes in the I.C.A.O. Standard Atmosphere. (After McDonald, J. E., *J. Meteorol.*, 17(3), 380, 1960. With permission.)

This equation is not amenable to direct solution because C_d is a function of V_g through its dependence on the Reynolds number (R) which is defined for spheres as

$$R = \frac{2 V_g r}{\nu} \tag{23}$$

in which ν is the kinematic viscosity of the fluid medium with units of cm²/sec. In order to overcome this problem, Equations 22 and 23 may be combined to yield

$$C_d R^2 = \frac{8 W}{\pi \rho_m \nu^2} \equiv Q \tag{24}$$

where W = the weight of the particle, namely $4/3\ \pi\ r^3\ \rho_s\ g$ and Q = a quantity as defined. McDonald[20] has provided a means of directly calculating V_g from Equation 23. It involves a calculation of Q from Equation 24 and a graphical determination of R from the calculated value of Q (Figure 7). A further aid to the necessary computations is provided by tabular data (Table 3).

In cases where $R \leq 1$ (i.e., $Q \leq 24$), Stoke's law becomes valid and V_g may be computed directly from

$$V_g = \frac{2\,\rho_s\, g\, r^2}{9\,\mu} \quad (25)$$

where μ = atmospheric dynamic viscosity (g/cm-sec) and $\mu = \nu\,\rho_m$.

Based on these computational procedures, McDonald[21] has computed terminal fall velocities and descent times for typical fallout particles produced by nuclear detonations in the atmosphere (Figures 8 and 9).

The case of nonspherical particles is more complex since the aerodynamic drag is also dependent on particle shape. This problem has been addressed to some extent by Bagnold,[19] who uses an empirically determined shape factor to convert the actual dimensions of particles to their spherical equivalents.

When there is need to calculate the depositional pattern of elevated particles, largely under the influence of gravitational settling, it is necessary to account for wind-direction shear. The problem then is one of calculating particle trajectories from the fall velocity and the wind vector.[22]

A basic application of the terminal fall velocity is that of estimating deposition from a cloud of particles in the air layer at the ground surface. The rate of deposition may be calculated by

$$\frac{\Delta S}{\Delta t} = \omega = V_g\,\bar{X}(x,y,0) \quad (26)$$

where S = mass of particles per unit of surface area (g/m²), t = time (sec), ω = deposition rate (g/m²-sec), V_g = fall velocity (m/sec), and $\bar{X}$ (x,y,0) = mean ground-level air concentration of particles (g/m³).

2. Dry Deposition

It has been demonstrated that small aerosol particles (<20 μm) and some gases can deposit on the ground surface at a rate which is greater than that which might be predicted from their gravitational settling velocities. This suggests that other mechanisms must be operating in such cases. Such mechanisms may include surface impaction, electrostatic attraction, adsorption, and chemical interaction.[2] These mechanisms can operate to remove small particles or gases from the near-surface atmosphere during precipitation-free periods and collectively, such processes lead to the phenomenon termed "dry deposition".

In practical situations calling for deposition estimates, investigators have generally opted for an experimental approach whereby the relationship between deposition and air concentration is determined empirically under specified conditions. The deposition rate of a specific aerosol or gas should be proportional to the ground-level air concentration. With this assumption, one may define a velocity of deposition (V_d) as

$$V_d = \frac{\Delta S/\Delta t}{\bar{X}(x,y,0)} = \frac{\omega}{\bar{X}(x,y,0)} \quad (27)$$

which is the same formulation as Equation 26, except that V_d is a measured parameter, applicable under a specified set of conditions.

A common experimental approach to the measurement of V_d is to generate an aerosol over an area of interest for a finite period of time (t) and measure the cumulative deposition (S) as well as the values of X(x,y,0) over time. In this case,

$$V_d = \frac{S}{\int_0^t X(t)\,dt} \approx \frac{S}{\bar{X}(x,y,0)\,t} \quad (28)$$

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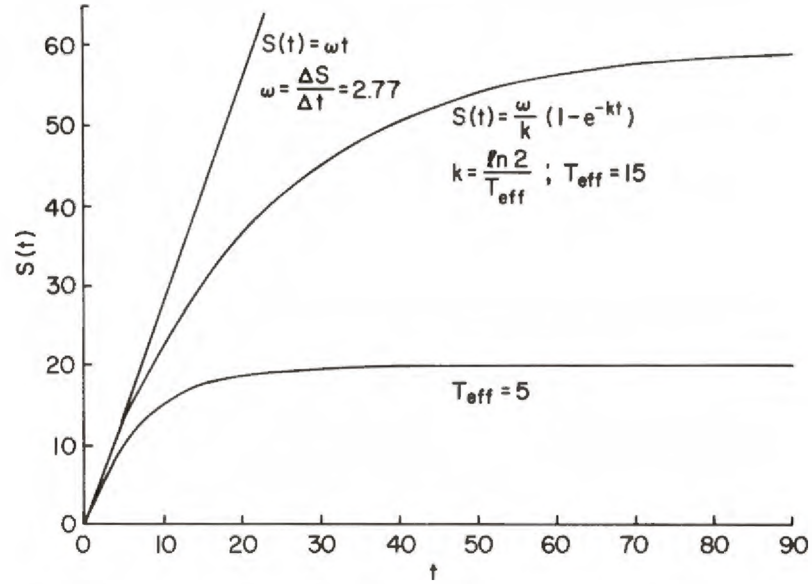

FIGURE 10. The relationship between deposition (S) and time (t) for various values of T_{eff}.

The preceding approach does not account for possible losses of material from the surface in question, but this is not a serious error as long as the time of the experiment is much shorter than the mean residence time of the particles or gas molecules on the surface. In some cases, such as the deposition of material on water or soil, the material may remain on the surface for extended periods of time. On the other hand, we are frequently interested in the deposition of material on vegetation so the foliage may represent the surface which is sampled and measured. The retention time of small particles or gases may not be very long for many types of vegetation. Figure 10 illustrates examples of these cases.

In the case where there is no loss mechanism from the surface, the retention is complete and the effective loss half-time, $T_{eff} = \infty$. Thus,

$$\frac{dS}{dt} = \omega - 0$$

$$dS = \omega\, dt \tag{29}$$

and

$$S = \omega \int dt$$

$$S = \omega\, t \tag{30}$$

when S = 0 at t = 0.

If there is a loss mechanism, the retention may be a first-order process such that it may be described by a loss rate constant k,

$$\frac{dS}{dt} = \omega - k\,S \tag{31}$$

where

$$k = \frac{\ln 2}{T_{eff}}$$

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Equation 31 may be integrated for the initial condition that S = 0 at t = 0 to yield

$$S = \frac{\omega}{k}\left(1 - e^{-kt}\right) \tag{32}$$

Note from Figure 10 that ω can be estimated from the line tangent to each curve at the origin and the ratio of ω to $\overline{X}$ is V_d (Equation 27). The larger the value of T_{eff} relative to the time over which data are collected to estimate S(t), the more accurately the value of ω can be estimated.

The numerical value of V_d is dependent upon a large array of variables. Such variables are associated with the nature of the particles or gases, characteristics of the surface, and meteorological conditions prevailing near the interface between the atmosphere and the surface. Variables associated with particles or gases affecting V_d include:

- Particle size
- Particle density
- Particle shape
- Electrostatic charge
- Surface chemistry
- Agglomeration with other particles

Important variables associated with the surface include:

- Texture
- Roughness
- Presence of hairs or other projections
- Electrostatic charge
- Surface chemistry
- Effective surface area
- Surface orientation

Airspeed profile, turbulence, temperature, and relative humidity are some of the potentially important meteorological variables. Because of such variables, V_d is a highly site specific, time-dependent parameter. Some empirically determined values of V_d are listed for various situations in Table 4.

In recent years, considerable progress has been made toward the development of theoretical concepts which can be applied to the prediction of deposition velocities.[33] Efforts to predict deposition velocity ordinarily account for particle size and density, as well as parameters which are sensitive to the wind profile, which in turn is governed by wind speed and surface characteristics. The pertinent parameters sensitive to the vertical wind profile are the friction velocity (u_*) and roughness height (z_0).

The friction velocity (u_*, cm/sec) may be determined for the usual case of turbulent flow over a rough surface from[2]

$$u_* = 0.4\, z \frac{d\bar{u}}{dz} \tag{33}$$

where 0.4 is von Karman's constant (empirically determined), z is the height in centimeters at which u_* is desired, and $d\bar{u}/dz$ = slope of a plot of wind speed vs. height at z. This relationship indicates proportionality between u_* and $d\bar{u}/dz$, and therefore, the dependence of u_* on the variables which affect $d\bar{u}/dz$, such as shear stress, kine-

Table 4
SOME DEPOSITION VELOCITIES MEASURED BY FIELD EXPERIMENTATION

Substance	Surface	Remarks	V_d (cm/sec)	Ref.
^{131}I	Grass	200—610 g grass/m^2	1.1—3.7	23
^{131}I	Clover leaves		0.5—1.3	23
^{131}I	Paper		0.3—2.0	23
^{131}I	Grass	153—246 g grass/m^2	0.6—1.0	24
^{131}I	Soil		0.4—0.8	24
^{131}I	Snow		0.2	24
^{131}I	Sticky Paper		0.2—0.6	24
^{131}I	Grass		1.2—2.1	25, 26
^{131}I	Soil		0.5—1.4	25, 26
^{131}I	Sticky Paper		0.1—1.5	25, 26
^{131}I	Water		1.4—2.3	25, 26
^{137}Cs	Water	<10 μm particles	0.9	25, 26
	Soil	<10 μm particles	0.04	25, 26
	Grass	<10 μm particles	0.2	25, 26
^{103}Ru	Water	<10 μm particles	2.3	25, 26
	Soil	<10 μm particles	0.4	25, 26
	Grass	<10 μm particles	0.6	25, 26
^{95}Zr-Nb	Water	<10 μm particles	5.7	25, 26
	Soil	<10 μm particles	2.9	25, 26
SO_2	Short grass		0.55	27
	Medium grass		0.77—1.19	27
	Soil		1.1	27
	Water		0.46	27
	Coniferous forest		<2	27
Ozone	Soil		0.84—1.76	27
	Grass		0.55	27
Ozone	Sand		0.14	27
^{238}Pu	Bean leaves	Exposure chamber, 0.5—1.8 μm particles	0.003—0.02	28
Pollens	Soil	Open field	2—15	29
^{141}Ce	Deciduous tree leaves	Calculated from fallout data	0.3—0.8	30
^{7}Be	Sea water		0.6—5.3	31
^{134}Cs, ^{141}Ce	Grass	Submicron aerosols	0.02—0.07	32
^{134}Cs, ^{141}Ce	Sagebrush	Submicron aerosols	0.15—0.18	32

matic air viscosity, air density, eddy viscosity, height above the surface, and the resistance to air flow provided by the surface.

Consideration of the roughness height (z_0) arises in the integration of Equation 33.

$$\bar{u}(z) = \frac{u_*}{0.4}\int \frac{dz}{z}$$

$$= \frac{u_*}{0.4} \ln z + \text{constant of integration}$$

Evaluating the constant of integration for $\bar{u} = 0$ when $z = z_0$, one obtains

$$\bar{u}(z) = \frac{u_*}{0.4} \ln\left(\frac{z}{z_0}\right) \tag{34}$$

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Table 5
EXPERIMENTAL VALUES FOR z_o AND u_* FOR VARIOUS SURFACES FOR $\bar{u}(2\ m) = 5$ m/sec

Surface	z_o(cm)	u_*(m/sec)
Smooth mud flats, ice	0.001	0.16
Smooth snow	0.005	0.17
Smooth sea	0.02	0.21
Level desert	0.03	0.22
Lawn to 1 cm high	0.1	0.27
Lawn to 5 cm high	1—2	0.43
Lawn to 60 cm high	4—9	0.60
Fully grown root crops	14	1.75

From Slade, D. H., Ed., Meteorology and Atomic Energy 1968, U.S. AEC Rep. TID-24190, U.S. Atomic Energy Commission, Washington, D.C., 1968.

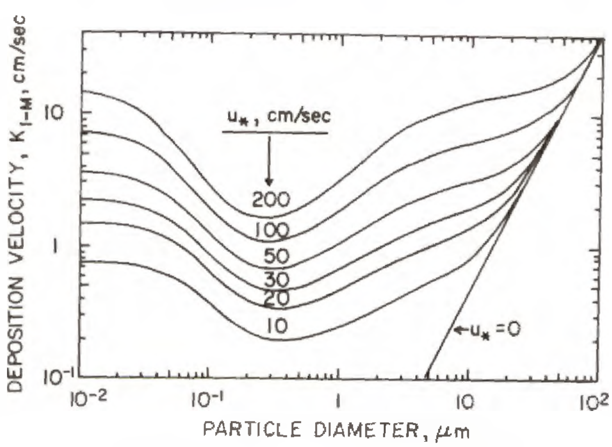

FIGURE 11. Predicted deposition velocities at 1 m for z_o = 3.0 cm and particle density = 1.5 g/cm³. *Note:* K_{I-M} has same meaning as V_d in text. (After Sehmel, G. A. and Hodgson, W. H., *ERDA Symp. Ser.* 38, 399, 1976.)

Thus the roughness height is that height where $\bar{u}$ becomes 0. Obviously then, z_0 is a function of the nature of the surface, taking on small values for smooth surfaces such as ice or water, and larger values for dense vegetation canopies. It is also a function of $\bar{u}(z)$, taking on smaller values as wind speed increases. Equations 33 and 34 may be combined and rearranged to show that

$$z_0 = \exp\left[\ln z - \frac{\bar{u}(z)}{z\left(\frac{d\bar{u}(z)}{dz}\right)}\right] \qquad (35)$$

Experimental measurements of the wind profile near the surface yields values for $\bar{u}(z)$ and $d\bar{u}(z)/dz$, and thus estimates of z_0 and u_*. For example, Table 5 gives some estimates of z_0 and u_* for various types of surfaces for $\bar{u}(2m) = 5$ m/sec.[2]

With estimates of u_* and z_0 in hand, one may calculate a predicted deposition velocity for particles of a specified diameter and density according to methods outlined by Sehmel and Hodgson.[33] For practical purposes, $\bar{u}$ and $d\bar{u}/dz$ may be measured at z =

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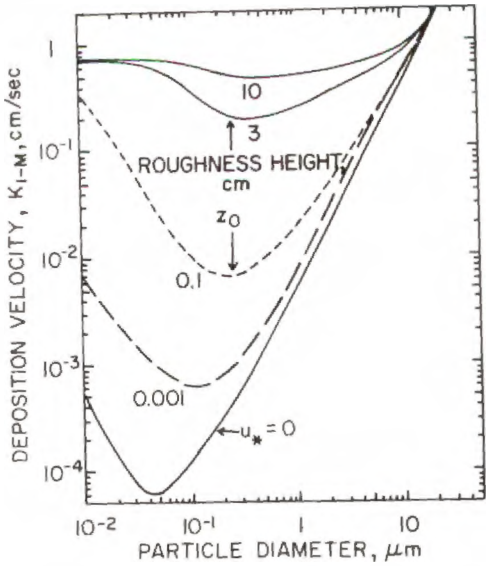

FIGURE 12. Predicted deposition velocities at 1 m for $u_* = 10$ cm/sec and particle density = 1.5 g/cm^3. *Note:* K_{I-M} has same meaning as V_d in text. (After Sehmel, G. A. and Hodgson, W. H., *ERDA Symp. Ser.* 38, 399, 1976.)

1 m, thus yielding an estimate of V_d for a height of 1 m. This procedure may not be adequate unless air concentrations of the aerosol are essentially independent of height near the surface. Figure 11 shows the relationship between particle diameter and deposition velocity for u_* values ranging from 10 to 200 cm/sec, when $z_0 = 3.0$ cm and particle density = 1.5 g/cm^3. Figure 12 summarizes the predicted relationships between particle diameter and deposition velocity for z_0 values ranging from 0.001 to 10 cm, when $u_* = 10$ cm/sec and particle density = 1.5 g/cm^3. Sehmel and Hodgson[33] provide similar plots for a range of u_* values extending from 10 to 100 cm/sec and a range of z_0 values from 0.001 to 10 cm, for particles of density 1.5 g/cm^3.

3. Cloud Depletion

The equations presented earlier in this chapter which dealt with the prediction of atmospheric dispersion did not consider the problem of aerosol depletion from a plume resulting from deposition. Having examined the problem of deposition and the concept of deposition velocity, the authors are now ready to consider a method of estimating plume or cloud depletion.[2] This method involves multiplication of the source strength term Q in Equations 1 to 4 by a cloud depletion factor, defined as

$$\frac{Q'_x}{Q'_0}$$

where Q'_0 is the original source term and Q'_x is the effective depleted source term at distance x. Values of Q'_x/Q'_0, which are functions of downwind distance, Pasquill stability type, and effective plume height, have been calculated from theoretical considerations for $V_d = 1$ cm/sec and $\bar{u} = 1.0$ m/sec (Figure 13). To estimate the cloud depletion factor for other values of V_d and $\bar{u}$, one may use the relation

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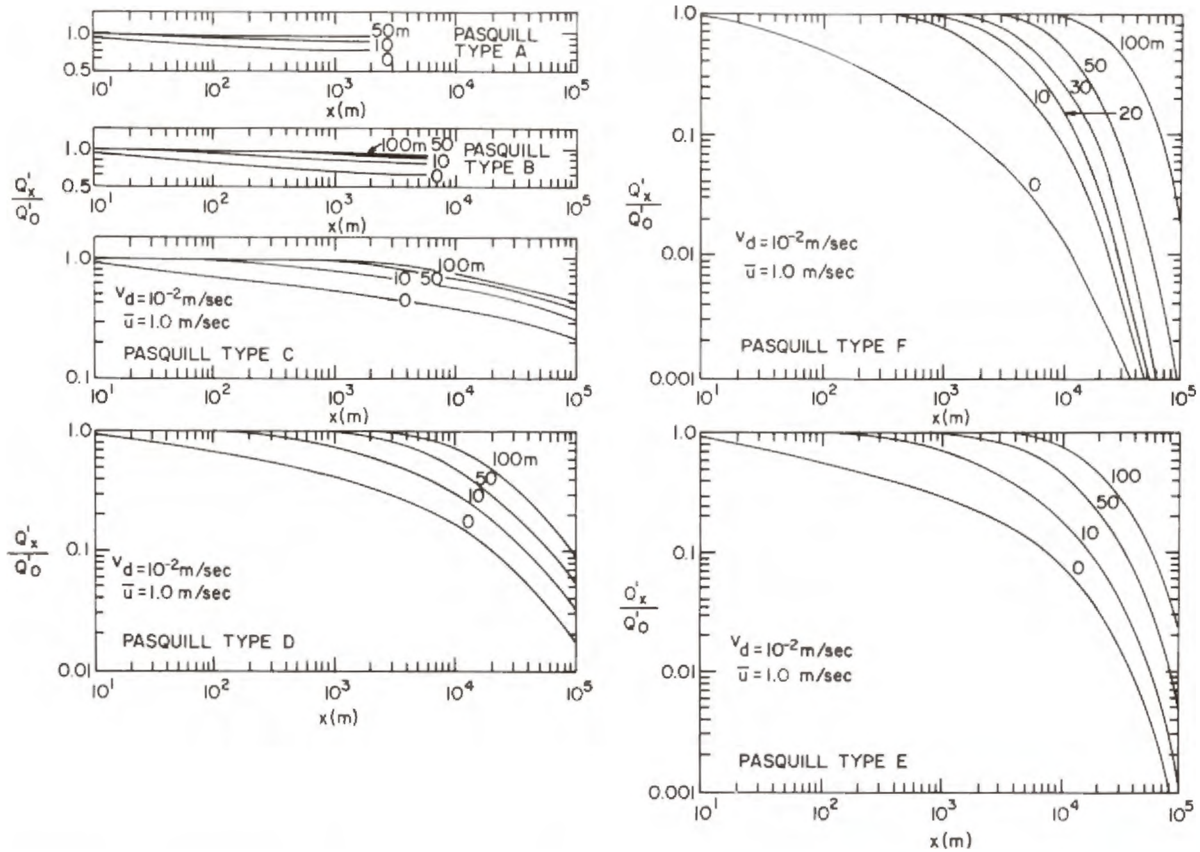

FIGURE 13. Source-depletion fraction (Q'_x/Q'_o) vs. distance (x) for a wind speed ($\bar{u}$) of 1.0 m/sec, a deposition velocity (V_d) of 10^{-2} m/sec, for source heights from 0 to 100 m above the ground and for various stability categories. (After Slade, D. H., Ed., Meteorology and Atomic Energy 1968, U.S. AEC Rep. TID-24190, U.S. Atomic Energy Commission, Washington, D.C., 1968.)

$$\left(\frac{Q'_x}{Q'_o}\right)_2 = \left(\frac{Q'_x}{Q'_o}\right)_1^{\bar{u}_1 V_{d_2}/\bar{u}_2 V_{d_1}} \tag{36}$$

where subscript 1 refers to the values found in Figure 13 and subscript 2 refers to the desired values.

4. Wet Deposition

Rain and snowfall are frequently important mechanisms of deposition for particles and gases. The general process, termed "precipitation scavenging" may be divided into in-cloud scavenging, called "rainout" or "snowout", and below-cloud scavenging, called "washout".[2,18] Washout generally becomes increasingly effective for particles greater than 1 μm in diameter, but the process is not very important for submicron particles. Rainout can involve submicron particles because different physical processes are involved. The theory and calculation of washout is somewhat better developed than that for rainout.

The process of washout obeys first-order kinetics, and thus,

$$\chi = \chi(o)e^{-\Lambda t} \tag{37}$$

where χ represents air concentration of a contaminant (μCi/m^3) and Λ is the washout coefficient in units of time^{-1}. The value of Λ is affected by the particle characteristics, as well as those of the falling water droplets.[2] For most practical purposes, Λ can be estimated with reasonable accuracy from the radius and density of the particles, and from the rate of precipitation (Figure 14). For aerosols having a value of $a^2\varrho$ (radius squared times density) of 40 to 50 μm^2 g/cm^3, Λ (sec^{-1}) can be estimated from the empirical data[2]

$$\Lambda = 1.6 \times 10^{-4} R_p^{0.8} \tag{38}$$

where R_p is the rate of rainfall in mm/hr.

The deposition rate from washout is given by

$$\omega = \Lambda \int_o^z \chi(z)dz \tag{39}$$

where ω = deposition rate (μCi/m^2-sec), Λ = washout coefficient (sec^{-1}), $\chi(z)$ = air concentration as a function of height z (μCi/m^3), and z = height from which the rain falls. Equation 39 may be superimposed on the Gaussian plume model to obtain ω as a function of the source term, wind speed, and diffusion parameters.[7] If χ is a function of time, as could well be the case due to a variable source term, or cloud depletion due to scavenging upwind from the point of interest, then the total deposition from washout is

$$S = \int_o^t \omega\, dt = \Lambda \int_o^t \int_o^z \chi(z,t)\,dz\,dt \tag{40}$$

where S is the time integrated deposition in μCi/m^2.

Equation 37 may be used to estimate cloud depletion due to washout. In this case,

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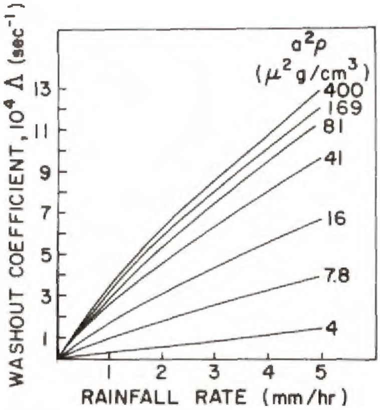

FIGURE 14. Washout coefficients calculated for various values of $a^2\rho$ (particle radius squared × density) as a function of the rainfall rate. (From Slade, D. H., Ed., Meteorology and Atomic Energy 1968, U.S. AEC Rep. TID-24190, U.S. Atomic Energy Commission, Washington, D.C., 1968.)

$$\chi' = \chi(x,y,z)e^{-\Lambda\left(\frac{x}{\bar{u}}\right)} \tag{41}$$

where χ' = the air concentration corrected for washout ($\mu Ci/m^3$), $\chi(x,y,z)$ = the predicted air concentration at coordinates x,y, and z based upon the plume model, x = downwind distance (m), and $\bar{u}$ = mean wind speed acting on the plume (m/sec).

Washout of gases involves consideration of molecular diffusion, vapor pressures, and solubilities of the gases in the rain droplets. These parameters may vary significantly for different gases, and this complicates predictive efforts. Engelmann has summarized some data on the ratio of washout coefficients to diffusivity for water soluble gases as a function of rainfall rate.[2a] Beilke[34] shows some data on washout coefficients for SO_2 and NO_2 vs. rainfall rate. The values are in the range of 10^{-4} to 10^{-2} sec^{-1} for rainfall intensities between 1 and 100 mm/hr. Several papers dealing with this subject are available in Precipitation Scavenging-1970.[18]

Washout of particles and gases by snowflakes occurs, but the basis for prediction of washout coefficients is apparently not well established. Some data suggest that snowflakes are more efficient scavengers of aerosol particles than raindrops,[2] and if true, this may be due to the increased surface area and lower fall velocities of snow crystals. There is some evidence to the contrary, however.[2] This may not be surprising in view of the multitude of shapes, fall velocities, electrical charges, and particle retention efficiencies that may be encountered. Sood and Jackson[35] have shown that scavenging efficiency decreases with snow crystal diameter and that particles of 0.3 to 0.5 μm diameter are scavenged less efficiently than smaller and larger particles. Washout coefficients for the gases bromine and inorganic iodine on the order of 3×10^{-6} and 5×10^{-8} sec^{-1}, respectively, have been measured for powder snow at a rate of 0.2 mm/hr.[2] These values are substantially lower than for rainfall and probably reflect reduced adsorption on the ice crystal surface as compared to liquid.

Predictive capability for in-cloud scavenging (rainout or snowout) is in an earlier state of development than washout. This is due in part to the complexity of the mechanisms involved, which include electrical effects, nucleation, diffusiophoresis, Brown-

ian motion, and velocity gradients. It may prove useful to approach this problem as was done for washout by stating

$$\chi = \chi(o)e^{-\psi t} \tag{42}$$

where ψ is the rainout coefficient having units of sec^{-1}. Few estimates of ψ have been made. However, Perkins et al.[36] used the novel approach of measuring deposition and cloud content of several cosmogenic radionuclides to estimate ψ. These investigators obtained values in the range of 10^{-4} to 5×10^{-3} sec^{-1}. The application of Equation 42 to estimate deposition would require knowledge of χ through the vertical extent of the cloud, as well as the cloud thickness. Another problem is that of possible time-dependencies of χ in the cloud due to processes other than rainout. Engelmann[37] has suggested an alternative modeling approach which is based on observed ratios of radionuclide concentrations in precipitation to those in air. Serious students of this problem should consult this latter work, as well as the earlier studies.

C. Resuspension

Resuspension refers to the process whereby small particles (usually < 50 μm diameter) are elevated into the airstream from the ground surface. Wind or other mechanical disturbances at the soil surface are the major causes of resuspension. Resuspended particles may be transported over a large range of distances from their origin prior to deposition. Particles in the respirable size range (< 10 μm) may be inhaled and this process may therefore be of considerable importance if the particles are contaminated with radionuclides or other potentially toxic substances. Since the soil surface is commonly a major reservoir of radionuclide contamination, resuspension of soil particles is a common mechanism of dispersal and a possible initiator of food chain transport.

Resuspension is one facet of a more general and older problem, wind erosion. Whereas resuspension as related to radionuclide transport has been studied intensively only in the past two decades, wind erosion has been broadly investigated since the 1930s. Most wind erosion studies have been motivated by concerns over the loss of agricultural topsoils. Such soils are extremely vulnerable to wind erosion when bare and dry and the Great Plains dust storms of the 1930s caused inestimable damage to the agricultural potential of this country. The voluminous wind erosion research has provided a useful basis for estimating soil transport, but the more recent studies have added some necessary steps to the specific problem of evaluating contaminant resuspension.

The factors which affect wind erosion and resuspension are numerous, and these may interact in a complex manner.[38] Some of the atmospheric variables that are important include

- Velocity
- Turbulence
- Density = f (temperature, pressure, humidity)
- Viscosity

Features of the soil and ground surface which require consideration include

- Texture (i.e., particle size distribution)
- Cohesiveness
- Moisture content
- Density

- Plant cover
- Ground surface roughness
- Topography

The distribution of soil grain sizes is of particular importance in that both erodibility and the mechanism of erosion is affected by particle size.[19,39]

Principal transport mechanism	Particle diameter (μm)	Relative erodibility
Airborne transport	<20	Nonerodible, except at very high wind speeds
	20—50	Difficultly erodible
Saltation	50—500	Highly erodible
	500—1000	Difficultly erodible
Surface creep	>1000	Nonerodible except at very high wind speeds

Only those particles less than 50 μm in diameter remain airborne for significant time periods because their settling velocities are small in relation to the turbulent motions of the air. Note that these particles are less erodible than larger ones. A major reason for this is that due to their small size the wind exerts a smaller drag force on them. However, once the smaller particles are set in motion, they are subject to significant spatial transport. Airborne transport and resuspension are essentially synonymous, thus resuspension is a measure of the airborne transport of smaller particles, and thus it normally involves only a fraction of the soil near the surface. That fraction is determined in part by the soil grain size distribution. The degree of airborne transport is also affected by the motions of larger particles, since these can dislodge the smaller ones from the surface.

Particles in the general size range of 50 to 1000 μm are large enough to catch wind motions and yet light enough to be elevated from the surface. However, these particles have appreciable settling velocities and thus return to the ground soon after being elevated. This results in a "hopping" motion and the process is termed "saltation". Saltation may account for a great deal of erosion. Saltating particles not only result in horizontal transport of medium-sized grains, but also dislodge other particles in a range of sizes upon impact with the surface. This impact may have considerable force if the wind velocity near the surface is high. Particles greater than 1 mm diameter are normally too heavy to be elevated by wind, but they may roll or slide along the surface by the mechanism of surface creep. This process may also be effective in dislodging other particles.

There are several possible approaches to the problem of estimating resuspension. Perhaps the simplest is the so-called "mass-loading" approach. If it can be assumed that all the dust suspended in the airstream originated from soil in the contaminated area of concern, the air concentration is simply estimated by

$$X = MC_r \tag{43}$$

where X = air concentration in μCi/m^3, M = air dust load in g/m^3, and C_r = concentration in the resuspendable fraction of the soil in μCi/g.

Values of M are relatively easy to measure using air filters, although large variations through time occur in response to soil condition and climatic variables. An average value of M for nonurban locations is roughly 4×10^{-5} g/m^3.[40] In contrast, dust clouds formed over bare fields by high winds may carry of the order of 1 to 10 mg soil per cubic meter.

Sampling of surface soil for the purpose of estimating C_r is not so simple. The major

problems are sampling depth and determination of the resuspendable soil fraction. If the contaminant is uniformly distributed with depth, then the sampling depth is less critical. However, this is seldom the case. Typically, a fresh deposit of radioactive particles will be confined initially to the top 1 or 2 mm of soil. In time, the particles will be distributed to greater depths. Deposition of uncontaminated soil and litter may effectively cover a surface deposit over a sufficient time period. Another problem lies in estimating the thickness of the soil layer that can be expected to be erodible under the prevailing atmospheric and ground surface conditions. For short-term predictions it would intuitively seem that a sampling depth of about 2 mm would be reasonable, since even relatively high erosion rates are generally less than 0.1 mm/day, although severe dust storms could remove up to 1 cm/day from bare fields.[41]

The determination of radioactivity in the suspendable soil fraction could be accomplished by dry sieving to isolate particles less than 50 μm for radioassay. However, agglomeration of individually suspendable particles in soil may render them nonsuspendable. Dry sieving may reasonably simulate the clod-shattering effects that may be caused by saltation and surface creep, and if so this method would seem reasonable.

The mass-loading approach would appear valid for contaminated areas sufficiently large to assume that the airborne dust originated from the contaminated area. This approach is not recommended, however, for small or larger areas exhibiting heterogeneous deposition patterns.

In view of substantial research which has been devoted to the erosion equations developed by agricultural scientists, these methods warrant close examination.[41] The basic erosion equation[42] is

$$E = f(I', K', C', L', V) \tag{44}$$

where E is the amount of erosion in tons per acre-year and a function of I' = soil erodibility index based on particle size distribution from dry sieving, K' = soil ridge roughness factor, C' = climatic factor, based on wind and precipitation patterns, L' = field length along the prevailing wind direction, and V = equivalent quantity of vegetation cover. Since E is a generally complex function of each of the five variables listed, a single predictive equation has not been developed. Thus, various charts and nomograms are used to calculate the erosion rate in a stepwise manner.[42] The value of E represents potential, rather than actual soil loss and the method is more useful for prediction of long-term average erosion rates than for short-term events.[43]

The major utility of Equation 44 is that it measures total soil loss. In order to apply this approach to resuspension, one may write[41]

$$F_r = f_r C_r E \left(7.1 \times 10^{-10} \frac{\text{g cm}^{-2}\ \text{sec}^{-1}}{\text{ton acre}^{-1}\ \text{year}^{-1}}\right) \tag{45}$$

where F_r = resuspension flux (μCi/cm^2-sec), f_r = fraction of the erosion flux that is resuspended, and C_r = concentration in the resuspendable fraction of soil (μCi/g).

According to some early work by Chepil,[38] values for f_r ranging from 0.03 to 0.38 were measured for heavy clay and loamy soils, respectively. The values of f_r were approximately proportional to the fraction of the soil comprised of particles less than 100 μm. More recent work, however, suggests considerable uncertainty in the actual values of f_r.[41]

A third approach for the evaluation of resuspension is use of the so-called "resuspension factor", defined as

$$R = \frac{X}{S} \tag{46}$$

where R = resuspension factor (m^{-1}), χ = air concentration ($\mu Ci/m^3$), and S = surface deposition ($\mu Ci/m^2$). This approach is strictly empirical in that it is based on the ratio of two measurements which should be more or less related. Once the resuspension factor concept began to appear in the literature, it quickly became apparent that the values of R were extremely variable, exhibiting a range of some 12 orders of magnitude (10^{-13} to $10^{-1}m^{-1}$). This range of variability precludes generic application of this approach and is reflective of the large number and relative importance of variables which control resuspension.

One of the earlier papers dealing with resuspension was prepared by Healy and Fuquay.[44] Based upon relatively simple, semiempirical equations, these authors estimated values of the resuspension factor as a function of particle diameter and wind speed. Although they did not define the resuspension factor per se, the values listed in their Table 3 amount to R as it is defined in Equation 46. Stewart[45] prepared one of the earlier reviews of measurements of the resuspension factor. These measurements were made opportunistically following contaminating events and in conjunction with designed experiments. Values for R in the range of 10^{-11} to $10^{-3}m^{-1}$ were observed, but the great majority of measurements yielded values over a smaller range, 10^{-7} to $10^{-5}m^{-1}$.

An obvious time-dependence for R exists in the case of surface deposits. It is intuitive that as the more suspendable fraction of the deposit is removed by resuspension, and as some of the deposit weathers deeper into the soil, the value of R will diminish. This was recognized by Stewart[45] and subsequently addressed in considerable detail by Anspaugh and co-workers[46] and by Oksza-Chocimowski[47]. Based upon data from the Nevada Test Site,[46] Anspaugh and colleagues developed an empirical equation that relates the resuspension factor to time following an initial deposit,

$$R(t) = R_o e^{-\lambda\sqrt{t}} + R_f \qquad (47)$$

where R(t) = time-dependent resuspension factor, R_o = the initial resuspension factor ($10^{-4}m^{-1}$), λ = 0.15 $day^{-0.5}$, t = time (day), and R_f = the final resuspension factor ($10^{-9}m^{-1}$). This formulation does not portray any fundamental understanding of the resuspension process, rather it is simply an expression which obeys the constraints of observed data. It implies that the resuspension factor has an initial value which subsequently declines with an effective weathering half-life that becomes increasingly longer with time. The addition of the term R_f indicates that the value of R will become essentially constant and equal to R_f some 20 years after the initial deposit is laid down (assuming λ = 0.15 $day^{-0.5}$ and R_f = $10^{-9}m^{-1}$). Although this approach is empirical, it is consistent with both intuition and observation. Clearly however, the parameter values cited above may not be appropriate for ecological systems that differ from those of the Nevada Test Site.

Subsequent to the publication of Anspaugh's model cited above, Oksza-Chocimowski[47] examined several models and data relevant to the time-dependency of the resuspension factor. The intent was to develop a generalized model which would incorporate the concept that the weathering half-time of R is time-dependent, and the initial and final resuspension factors, if known, may be used as constraints in the model. This author developed equations which predict both weathering half-times and resuspension factors as functions of both time after deposition and the ratio of the initial to final resuspension factor. This approach appears promising, but the site-specificity of the initial and final resuspension factors imposes data requirements which likely cannot be met, except in a few isolated cases. Of particular difficulty is the ability to predict the final resuspension factor.

Another approach to the estimation of resuspension is the theoretical one which attempts to analyze the forces acting upon soil grains. For a uniform field of particles

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of known diameter and density, one may calculate the threshold wind velocity for the initiation of movement.[19] This involves equating the moment about the soil grain pivot point due to the particle weight to the moment due to the drag force exerted by the wind. One can extend these concepts further to estimate the rate of saltation as a function of wind speed and particle characteristics, and finally, to the rate of resuspension, using the assumption that the resuspension flux is proportional to the energy imparted to the ground surface by saltating particles.[48] Application of this approach, however, requires several tenuous assumptions and some of the constants in the equations are subject to the numerous variables affecting the resuspension process. In view of this, the theoretical approach is probably no more useful than empirical measurements for predictive purposes. The main utility of such theoretical analysis in this case is the possibility for a deeper understanding of the physical processes involved in soil erosion.

There is clearly a need to conduct further research over a wide spectrum of ecosystems and environmental conditions if credible, generally applicable models of resuspension are to be obtained. The process of resuspension can probably be adequately modeled for a few well-studied systems, such as the Nevada Test Site, but workers are not well prepared to model the process in most other localities, especially for a range of conditions. Since resuspension is frequently one of the more important radionuclide transport pathways, weaknesses in this area may extend to the whole process of radionuclide transport and dose estimation.

D. Sorption

Sorption is a general term that refers to the process of taking up and holding of material either by adsorption or absorption. One is generally concerned with the taking up of material that is dissolved or suspended in a fluid medium such as air or water by a solid surface. Since the process of sorption occurs at the interface between two phases, we are immediately confronted with the physics and chemistry of surfaces. Use of the term sorption avoids the distinction between adsorption, the strictly surficial adhesion of materials, and absorption, which implies penetration of the solid by the substance in question. In many practical situations in radioecology, one is unable to make the distinction between these processes and in such cases, the term sorption is used. Occurrence of sorption usually implies a higher concentration of a given substance at the solid-fluid interface than in the bulk of the fluid medium.

In order for materials in a fluid medium to have the opportunity to become sorbed, they must have some finite probability of being in the vicinity of a surface, and this probability increases with the concentration of material in the fluid, the amount of surface area, and the rate at which fresh fluid is presented to the surface. In order for the material to be preferentially retained by the surface, there must exist a force or combination of forces which bind the material to the surface. Such binding forces include

- Molecular attraction (van der Waals forces)
- Electrostatic attraction
- Chemisorption
- Capillary forces

Molecular attraction, sometimes called "physical absorption", may ultimately relate to electrostatic forces, in that all molecules may behave as oscillating dipoles and as such, can mutually orient in ways which cause attraction. These forces are comparatively weak and the van der Waals forces are generally characterized by low heats of

adsorption.[49] Electrostatic forces of a stronger kind may provide binding when dipolar molecules, ions, or charged particles are held by a surface having opposite electrical charge. Ordinary ion exchange reactions involve this form of electrical or ionic binding. Chemisorption refers to actual chemical bonding between the surface and the material in question. This form of binding generally involves larger heats of absorption and the reaction may not be reversible unless considerable energy is supplied to the system. Some surfaces are porous, and the pore spaces may be filled with water. Such surfaces may bind materials through the capillary forces of surface tension between the liquid and solid surfaces.

A most common form of radionuclide transport from one environmental medium to another involving sorption is the transfer of radioactive material between a solution phase (water) and a solid phase (soil, detritus, plant cells, etc.). Ordinarily, the distribution of a radionuclide between the solid and liquid phases involves an exchangeable reaction, which proceeds until an equilibrium is established. This may be represented as follows:

$$A_\ell + M \rightleftharpoons AM \tag{48}$$

where A_ℓ represents an atom in the liquid phase, M represents the surface material, and AM represents the condition in which A is sorbed to M. This exchange reaction may also be symbolized in terms of the kinetics of a compartmental system, which is more consistent with our general approach in this chapter.

$$\begin{tikzcd} \boxed{q_\ell} \arrow[r, shift left, "k_1"] & \boxed{q_m} \arrow[l, shift left, "k_2"] \end{tikzcd}$$

This conceptual model implies that q_ℓ = amount of radionuclide in the liquid phase, q_m = amount of radionuclide in the solid phase, and k_1 and k_2 = rate constants describing the speeds of transfer in units of time^{-1}. This model also assumes first-order kinetics, in that the rate of sorption is proportional to q_ℓ and the rate of solution is proportional to q_m. While not all systems will follow this behavior, many will, and for the time being the authors shall assume this to be the case. The values of the rate constants are determined by a plethora of conditions, such as temperature, pH, the amount of surface available, the chemical nature of the radionuclide and surface, and so on.

Assuming constancy of these factors, however, the authors will treat k_1 and k_2 as constants, characteristic of the system in question. The differential equations which describe this system are

$$\frac{dq_\ell}{dt} = k_2\, q_m - k_1\, q_\ell \tag{49}$$

and

$$\frac{dq_m}{dt} = k_1\, q_\ell - k_2\, q_m \tag{50}$$

Equations 49 and 50 may be solved, assuming that $q_\ell + q_m = q(0)$, by integrating to obtain q_ℓ and q_m as functions of time after the addition of q(0) quantity of radionuclide to the liquid phase. Thus, assuming that $q_\ell = q(0)$ and $q_m = 0$ at $t = 0$,

$$q_\ell = \frac{k_2\, q(0)}{k_1 + k_2} + \frac{k_1\, q(0)}{k_1 + k_2}\, e^{-(k_1 + k_2)t} \tag{51}$$

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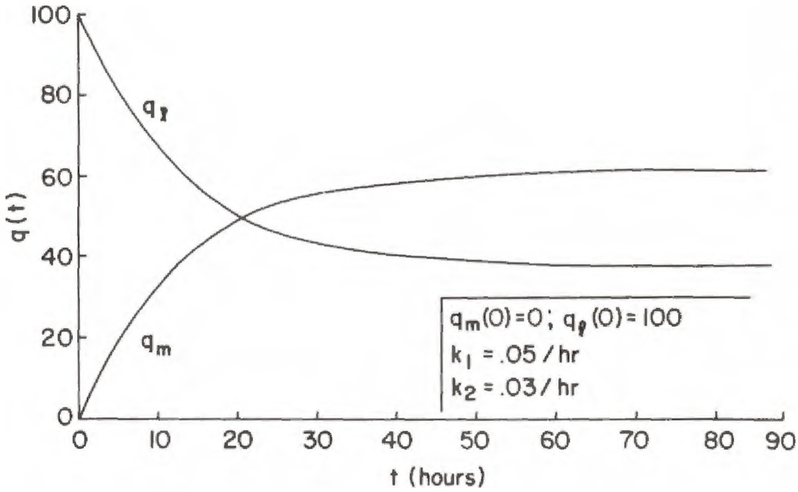

FIGURE 15. Curves for a two-compartment closed system with interchange. First-order kinetics are assumed. Initial values and rate constants for the system are arbitrary.

and

$$q_m = \frac{k_1\,q(0)}{k_1 + k_2}\left[1 - e^{-(k_1 + k_2)t}\right] \tag{52}$$

These equations yield curves of the form shown in Figure 15, for arbitrarily assigned values of q(0), k_1 and k_2. Note that the ratio of q_m to q_ℓ at equilibrium is governed by the relative values of k_1 and k_2. At equilibrium,

$$\frac{q_m}{q_\ell} = \frac{k_1}{k_2} \tag{53}$$

This is consistent with the concept that at equilibrium, the rate of sorption, $q_\ell\,k_1$ is equal to the rate of solution, $q_m k_2$. In addition, the rapidity with which equilibrium is established is governed by the rate constant for the exchange reaction (k_{ex})

$$k_{ex} = k_1 + k_2 \tag{54}$$

In practice, we are generally more concerned with the ratio of concentrations in adjacent media than in the ratio of total amounts. The ratio of concentrations at equilibrium is frequently called the "distribution coefficient", K_d, defined as

$$K_d = \frac{(\text{activity/g})\,\text{solid phase}}{(\text{activity/m}\ell)\,\text{liquid phase}} \tag{55}$$

$$= \frac{q_m\,M_\ell}{q_\ell\,M_m} = \frac{k_1\,M_\ell}{k_2\,M_m} \tag{56}$$

where M_ℓ refers to the total volume of the liquid phase in milliliters and M_m refers to the total mass of the solid phase in grams. The measurement of K_d in the laboratory or in the field is a practical means of measuring the tendency of solids to sorb materials from solution. Table 6 lists some K_d values of selected radionuclides for various soils and sediments.

Table 6
EXAMPLES OF MEASURED DISTRIBUTION COEFFICIENTS (K_d) FOR SELECTED RADIONUCLIDES IN SOILS AND SEDIMENTS

Material description	Conditions	Radionuclide	K_d	Ref.
Sediments				
Mediterranean	16—32μm	^{90}Sr	250	50
	4—8μm	^{90}Sr	930	50
	16—32μm	^{59}Fe	1.0×10^4	50
	4—8μm	^{59}Fe	1.8×10^4	50
	16—32μm	^{60}Co	5.4×10^4	50
	4—8μm	^{60}Co	8.2×10^4	50
	16—32μm	^{144}Ce	7.3×10^3	50
	4—8μm	^{144}Ce	1.5×10^4	50
Wadden Sea	16—32μm	^{60}Co	6.5×10^3	50
	4—8μm	^{60}Co	4.3×10^4	50
	16—32μm	^{144}Ce	1.2×10^4	50
	4—8μm	^{144}Ce	5.4×10^4	50
Guadalupe River		^{90}Sr	2.9×10^3	51
		^{137}Cs	2.4×10^4	51
Clays				
Illite	pH 6; 1 hr contact	^{137}Cs	2.7×10^4	52
	pH 6; 3 day contact	^{137}Cs	1.4×10^5	52
	pH 6; 7 day contact	^{137}Cs	1.8×10^5	52
	pH 6; 1 hr contact	^{60}Co	408	52
	pH 9; 1 hr contact	^{60}Co	3.6×10^3	52
	pH 6; 7 day contact	^{60}Co	6.4×10^3	52
	pH 9; 7 day contact	^{60}Co	2.4×10^4	52
Kaolinite	pH 6; 1 hr contact	^{137}Cs	2.9×10^3	52
	pH 9; 1 hr contact	^{137}Cs	1.4×10^4	52
Vermiculite	pH 6; 8 day contact	^{60}Co	7.7×10^3	52
	pH 9; 8 day contact	^{60}Co	440	52

Examination of the literature leads to the conclusion that the K_d is a function of many physical and chemical variables of the solid, the liquid, and the radionuclide. As a result, K_d values, while assumed to be rather constant for a given system under specified conditions, vary over many orders of magnitude for different situations. An important variable is the grain size and surface area presented by the solid. Table 7 gives a classification scheme for soil particles used by the International Soil Science Society, and also some estimates of particle numbers and surface area in a gram of each soil type. Since surface adsorption capability must be closely related to surface area in contact with the solution, it follows that clays will likely have much greater K_d values than sands of similar surface chemistry. Colloids represent even smaller particles (0.001 to 0.1 μm), with correspondingly greater surface area per gram and greater adsorptive capacity.

Clay mineral and organic particles of colloidal size usually represent the major adsorptive component of soils. The surfaces of these particles are usually negatively charged and attract water molecules as well as cations from solution. The capacity of soils and sediments to absorb cations and hold them is termed the "cation exchange capacity", usually expressed in meq/100g. Cation exchange capacity is dependent upon the physical and chemical nature of the soil particles, as well as of the liquid phase. Cations may replace one another on colloid surfaces, and the replacement power varies with the cation. Such replacement depends on relative concentration of ions, the charge number, and the speed of movement or activity of the different ions. The replacing power of some of the more common ions is, in descending order: H >

Table 7
THE INTERNATIONAL SOIL SCIENCE SOCIETY SYSTEM OF CLASSIFYING SOIL PARTICLES, AND ESTIMATES OF PARTICLE NUMBERS AND SURFACE AREA IN A GRAM OF MATERIAL

Description	Diameter (μm)	Number of particles/g	Surface area (cm^2/g)
Coarse sand	200—2,000	720	23
Fine sand	20—200	46,000	91
Silt	2—20	5.8×10^6	454
Clay	<2	9.0×10^{10}	8.0×10^6

From Millar, C. E., Turk, L. M., and Foth, H. D., *Fundamentals of Soil Science*, 4th ed., John Wiley & Sons, New York, 1965. With permission.

Sr > Ra > Ca > Mg > Cs > Rb > K > NH_4 > Na > Li.[53] In view of these principles, it is not surprising that different radionuclides may be sorbed to a given soil to differing degrees.

Since surfaces have a finite capacity to adsorb elements, the K_d value only holds over a certain range of solution concentrations. As long as the solution is relatively dilute, an increase in the solution concentration will result in a corresponding increase in the concentration of the solid phase, and the K_d remains constant. However, a point may be reached with concentrated solutions where the surface becomes saturated and the K_d decreases with solution concentration. Fortunately, in most situations involving radionuclides, the solutions are very dilute and K_d values are normally independent of the radionuclide concentration.

Equations 49 through 52 imply first-order kinetics. While many systems exhibit this form of kinetic behavior, some do not. For example, some systems behave as a power function,[54]

$$q_\ell = q_\ell(1)\, t^{-P} \tag{57}$$

and

$$q_m = q_\ell(1)\,(1 - t^{-P}) \tag{58}$$

where q_ℓ = the quantity of radionuclide in the liquid phase, $q_\ell(1)$ = the quantity of radionuclide in the liquid phase at unit reference time, q_m = the quantity of radionuclide in the solid phase, P = a constant, characteristic of the system, and t = time (multiples of the unit reference time). This type of behavior implies that the rate parameters governing exchange are not constant, but rather are changing with time. It may also suggest a complex surface, absorption, and possibly several mechanisms of uptake and retention.

The passage of radionuclides across biological membranes involves absorption of molecules, atoms, ions, and sometimes, tiny colloidal particles. Such absorption may be active or passive, depending upon whether or not energy is expended by the organism to achieve absorption. Typically, energy is required for absorption that operates against a concentration gradient. Membranes can exhibit remarkable selectivity in allowing or not allowing the passage of material. Such selectivity is related to the size of the materials in solution or suspension, the chemical nature of such materials, and

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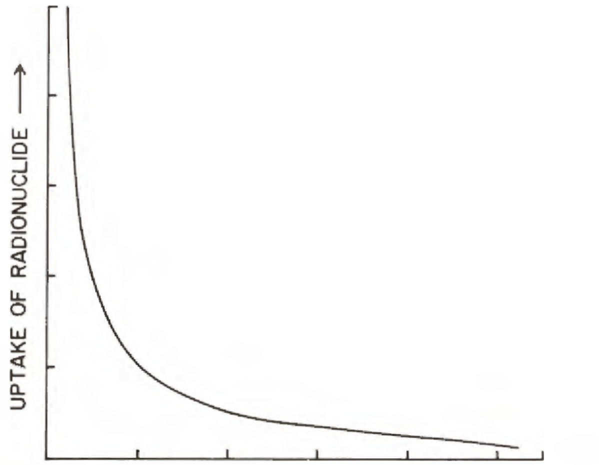

FIGURE 16. Typical form of the reduction in uptake of a radionuclide with an increase in the concentration of a competing, analogous element. Curve is of the form XY = constant.

the presence of competing substances in the solution phase. The presence of competing substances has special quantitative significance in the case of radionuclides which have nutrient element analogues and this phenomenon deserves further discussion.

It was mentioned in Volume I, Chapter 5 that the uptake of radionuclides of Sr, Ba, and Ra is affected by the presence of Ca. Similarly, uptake of ^{131}I is affected by stable iodine and the passage of Cs isotopes is influenced by potassium. These effects are observed in passage of radionuclides from soil to plants, from plants to animals, or in virtually any transfer involving absorption through a biological membrane. The general nature of this effect is a reduction in the sorption or uptake of the radionuclide with an increase in the concentration of the competing nutrient element (Figure 16). Competing elements are usually analogous, chemically, to the radionuclide in question. Frequently, a plot of radionuclide uptake (Y) vs. competing element concentration (X) yields a curve of the form:

$$X\,Y = \text{constant} \tag{59}$$

A log-log plot of data exhibiting this behavior should yield a straight line with a slope of −1.

In 1956, Comar and colleagues[55] published the concept of the "observed ratio" (OR), defined as

$$OR = \frac{X_s^*/E_s}{X_p^*/E_p} \tag{60}$$

where X_s^* = amount of radionuclide in a sample, E_s = amount of analogous nutrient element in a sample, X_p^* = amount of radionuclide in the precursor, and E_p = amount of analogous nutrient element in the precursor. Examples of sample/precursor systems include plant/soil, animal tissue/food, milk/plasma, and urine/plasma. In sample/precursor systems which exhibit no discrimination between the radionuclide and the analogous element, the OR is close to unity. On the other hand, OR values less than unity imply discrimination against the radionuclide as compared to the analogous ele-

Table 8
EXAMPLES OF SOME OBSERVED RATIOS (OR) REPORTED FOR STRONTIUM/CALCIUM TRANSPORT IN FOOD CHAINS[57,58]

System	OR	Comments
Plant tissue/soil	0.9—1.0	OR values dependent on plant part
Fish muscle/water	0.5—1.0	OR dependent on [Ca^{++}] in water
Fish bone/water	0.5	
Milk/diet	0.08—0.16	Cows, goats, and pigs
Muscle/diet	0.2—0.5	Domestic animals
Poultry bone/diet	0.6	
Egg yolk/diet	0.6	
Egg white/diet	1.5	
Human bone/diet	0.25	Adults
Human bone/diet	0.5	1-year olds
Human bone/diet	0.8—1.0	0—3-month olds
Human urine/diet	0.4—0.8	OR dependent on Ca in diet
Mammalian bone/diet	0.14—0.57	Various species

ment. An OR value exceeding unity would imply discrimination in favor of the radionuclide. Equation 60 may be rearranged as

$$X_s^* E_p = OR\, X_p^* E_s \qquad (61)$$

If one takes the terms on the right-hand side of the above equation as constants, then Equation 61 is analogous to Equation 59. This implies that if the OR value is constant and independent of the other terms in Equation 60, then an increase in E_p will lead to a corresponding decrease in X_s^*. Many experimental examples of this relationship exist. Table 8 gives a few examples of OR values for Sr/Ca.

The OR relationship between strontium and calcium has been notably consistent and successfully applied to the modeling of strontium passage through food chains.[57,58] However, the OR approach has met with only limited success in the case of cesium and potassium, and there are numerous examples that suggest total departure from this concept. Since the OR relationship is strictly empirical and does not describe the processes involved in radionuclide sorption, it is not surprising to find deviations.

A comprehensive treatment of sorption phenomena should also address the transfer of particles and gases in the gaseous phase to solid surfaces. For most predictive purposes, the concepts and equations presented earlier in this chapter under "Deposition" are perhaps adequate. The authors have not attempted a theoretical description of the phenomena, but instead suggest reference to the more basic literature on surface chemistry and physics. In addition, specific literature on the exchange of gases and particles between the atmosphere and solid surfaces is available.[13,59,60]

E. Ingestion

Ingestion is the process of taking food and sometimes other material into the stomach, resulting in selective absorption of nutrients into the body of the animal. It represents a process of major importance in the passage of many radionuclides through food chains. This process is of generally greatest importance for those radionuclides which are easily absorbed and which are chemically similar to essential nutrient elements. It is of lesser importance for highly insoluble radionuclides, or for any radio-

nuclide that may be chemically or physically bound to a substance that is not broken down in the digestive tract so as to permit absorption. Ingestion of radioactive materials may lead to deposition within internal tissues, which can greatly increase the biological consequences of the energy released in the decay of such materials. This is especially true for radionuclides that emit particulate radiation of comparatively low penetrating power, such as alpha and weak beta particles. Even the ingestion of insoluble radionuclides that are poorly absorbed can produce an enhanced radiation hazard, namely the irradiation of cells in or near the GI tract.

The quantitative components of radionuclide ingestion include the rate of consumption of food, water or other material, the concentration of radionuclide in the ingested material, and the assimilation fraction. The rate at which a radionuclide is ingested from a given source (i) is

$$R_i = r_i C_i \tag{62}$$

where R_i = ingestion rate (μCi/t), r_i = consumption rate (g/t), aud C_i = radionuclide concentration in consumed material (μCi/g). In most situations, we must be concerned with radionuclide ingestion through a number of sources. The total ingestion rate (R) is

$$R = \Sigma R_i \tag{63}$$

and

$$R = \sum_i r_i C_i \tag{64}$$

Here, the authors are simply evaluating the radionuclide ingestion rate from each source and summing them. Sources may include a variety of food items, soil, water, and possibly other materials. Each material may have a representative ingestion rate and radionuclide concentration. The relative importance of the ith item is r_iC_i/R. Obviously, r_i and C_i are never constant in time and space, therefore these terms are usually estimated from sampling over some domain of time and space. For our simplest deterministic models, mean values of r_i and C_i are used. If one has sufficient data to estimate the occurrence distributions of these parameters, one may be able to develop stochastic or probabilistic models.

Equation 64 only gives the rate at which a given radionuclide enters the GI tract. In most modeling applications, we are concerned with the rate at which the radionuclide enters a given tissue, organ, or group of organs such as the body as a whole (Figure 17). To estimate the rate at which the radionuclide enters the body tissues, one simply multiplies the ingestion rate by the assimilation fraction (f_1).

$$\begin{aligned} R_{body} &= R_{ingestion}\, f_1 \\ &= f_1 \sum_i r_i C_i \end{aligned} \tag{65}$$

The parameter f_1 refers to the fraction of ingested material which is absorbed and crosses the wall of the GI tract to enter the blood or other body fluids. The value of f_1, which must be estimated from experimental data, is a function of the physical/chemical properties of the radionuclide, the nature of the ingested material, and the physiology of the organism. The nonabsorbed fraction, 1-f_1, is eliminated from the GI tract as a component of the fecal mass.

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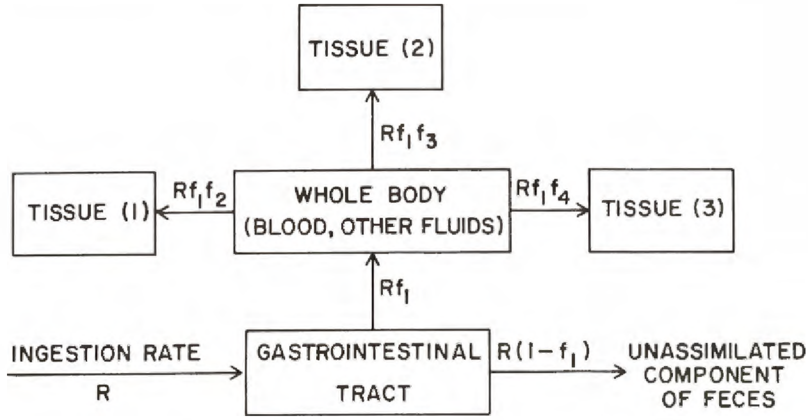

FIGURE 17. Schematic representation of a simple ingestion model in which R is the radionuclide ingestion rate, f_1 is the fraction absorbed by the body, and f_2, f_3, and f_4 represent fractions of the absorbed material which go to various tissues.

This concept can be extended further to describe the rate at which an ingested radionuclide enters a specific tissue,

$$R_{tissue} = R_{body} f_2$$

$$= f_1 f_2 \sum_i r_i C_i \qquad (66)$$

In this case, f_2 is the fraction of the material entering the body which goes to a specific tissue (Figure 17). Thus, one may generalize the ingestion model as follows:

$$R_j = a_j \sum_i r_i C_i \qquad (67)$$

where R_j = rate of radionuclide entry into the jth tissue and $a_j = f_1 f_{j+1}$ = fraction of the ingested radionuclide which is assimilated and goes to the jth tissue.

It is important to recognize that the terms in Equation 67 are not always independent, even though they are usually treated as such. The principal dependency is the effect of r_i on f_1 (and therefore, a_j). If the rate of food ingestion (r_i) increases, then the residence time of material in the gut may decrease, possibly decreasing the value of f_1. Further, the intake rate of competing elements will increase with r_i, again with the possible result being a decrease in f_1. This dependency is most likely to exist for radionuclides that have nutrient element analogues.

Another possible dependency in Equation 67 is the effect of the nature of material ingested on f_1 (and therefore, a_j). For example, a radionuclide incorporated within the tissue of a food substance may have a higher f_1 value than that of the same radionuclide superficially attached to a food substance. This difference implies a more soluble chemical form for the material incorporated within the tissues of the food substance. Another example might be the availability of a radionuclide ingested with food as compared to that ingested with soil or sediment. For instance, the normally soluble cesium isotopes can bind with clay minerals so tenaciously that they can be largely unavailable for absorption if ingested in that form. For cases where f_1 is dependent upon the type of material ingested, Equation 67 may be modified as follows:

$$R_j = f_{j+1} \sum_i r_i C_i f_{1i} \qquad (68)$$

Table 9
ASSIMILATION FRACTIONS FOR VARIOUS ELEMENTS AS RECOMMENDED BY THE INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION

Element	Organ of reference	f_1	a
H	Whole body	1.0	1.0
Li	Whole body	1.0	1.0
Be	Whole body	2×10^{-3}	2×10^{-3}
B	Whole body	0.9	0.9
C	Whole body	1.0	1.0
N	Whole body	1.0	1.0
O	Whole body	1.0	1.0
F	Whole body	1.0	1.0
Ne	Whole body	1.0	1.0
Na	Whole body	1.0	1.0
Mg	Whole body	0.1	0.1
Al	Whole body	0.1	0.1
Si	Whole body	0.85	0.85
P	Whole body	0.75	0.75
	Bone	0.75	0.38
S	Whole body	1.0	1.0
Cl	Whole body	1.0	1.0
A	Whole body	1.0	1.0
K	Whole body	1.0	1.0
	Muscle	1.0	0.65
Ca	Whole body	0.6	0.6
	Bone	0.6	0.54
Sc	Whole body	10^{-4}	10^{-4}
Ti	Whole body	10^{-4}	10^{-4}
V	Whole body	0.02	0.02
Cr	Whole body	<0.005	<0.005
Mn	Whole body	0.1	0.1
	Liver	0.1	0.02
Fe	Whole body	0.1	0.1
	Liver	0.1	0.013
Co	Whole body	0.3	0.3
	Liver	0.3	7×10^{-3}
Ni	Whole body	0.3	0.3
	Bone	0.3	0.15
Cu	Whole body	0.28	0.28
Zn	Whole body	0.1	0.1
	Liver	0.1	0.035
Ga	Whole body	$<10^{-3}$	$<10^{-3}$
Ge	Whole body	<0.01	<0.01
As	Whole body	0.03	0.03
Se	Whole body	0.9	0.9
Br	Whole body	1.0	1.0
Kr	Whole body	1.0	1.0
Rb	Whole body	1.0	1.0
	Muscle	1.0	0.45
Sr	Whole body	0.3	0.3
	Bone	0.3	0.09
Y	Whole body	$<10^{-4}$	$<10^{-4}$
Zr	Whole body	$<10^{-4}$	$<10^{-4}$
Nb	Whole body	$<10^{-4}$	$<10^{-4}$

Table 9 (continued)
ASSIMILATION FRACTIONS FOR VARIOUS ELEMENTS AS RECOMMENDED BY THE INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION

Element	Organ of reference	f_1	a
Mo	Whole body	0.8	0.8
	Liver	0.8	0.08
Tc	Whole body	0.5	0.5
Ru	Whole body	0.03	0.03
	Kidney	0.03	6×10^{-3}
Rh	Whole body	0.2	0.2
Pd	Whole body	0.2	0.2
Ag	Whole body	0.01	0.01
Cd	Whole body	$<2.5 \times 10^{-4}$	$<2.5 \times 10^{-4}$
	Liver	$<2.5 \times 10^{-4}$	$<1.9 \times 10^{-4}$
In	Whole body	$<2 \times 10^{-3}$	$<2 \times 10^{-3}$
Sn	Whole body	0.05	0.05
Sb	Whole body	0.03	0.03
Te	Whole body	0.25	0.25
I	Whole body	1.0	1.0
	Thyroid	1.0	0.3
Xe	Whole body	1.0	1.0
Cs	Whole body	1.0	1.0
	Muscle	1.0	0.4
	Kidney	1.0	0.01
	Liver	1.0	0.07
	Bone	1.0	0.04
Ba	Whole body	0.05	0.05
	Bone	0.05	0.035
La	Whole body	$<10^{-4}$	$<10^{-4}$
Ce	Whole body	$<10^{-4}$	$<10^{-4}$
	Liver	$<10^{-4}$	$<2.5 \times 10^{-5}$
Pr	Whole body	$<10^{-4}$	$<10^{-4}$
Nd	Whole body	$<10^{-4}$	$<10^{-4}$
Pm	Whole body	$<10^{-4}$	$<10^{-4}$
Sm	Whole body	$<10^{-4}$	$<10^{-4}$
Eu	Whole body	$<10^{-4}$	$<10^{-4}$
Gd	Whole body	$<10^{-4}$	$<10^{-4}$
Tb	Whole body	$<10^{-4}$	$<10^{-4}$
Dy	Whole body	$<10^{-4}$	$<10^{-4}$
Ho	Whole body	$<10^{-4}$	$<10^{-4}$
Er	Whole body	$<10^{-4}$	$<10^{-4}$
Tm	Whole body	$<10^{-4}$	$<10^{-4}$
Yb	Whole body	$<10^{-4}$	$<10^{-4}$
Lu	Whole body	$<10^{-4}$	$<10^{-4}$
Hf	Whole body	$<10^{-4}$	$<10^{-4}$
Ta	Whole body	$<10^{-4}$	$<10^{-4}$
W	Whole body	0.1	0.1
Re	Whole body	0.5	0.5
Os	Whole body	0.1	0.1
Ir	Whole body	0.1	0.1
Pt	Whole body	0.1	0.1
Au	Whole body	0.1	0.1

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Table 9 (continued)
ASSIMILATION FRACTIONS FOR VARIOUS ELEMENTS AS RECOMMENDED BY THE INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION

Element	Organ of reference	f_1	a
Hg	Whole body	0.75	0.75
	Kidney	0.75	0.26
	Liver	0.75	0.11
Tl	Whole body	0.45	0.45
Pb	Whole body	0.08	0.08
	Bone	0.08	0.02
	Liver	0.08	6.4×10^{-3}
	Kidney	0.08	0.01
Bi	Whole body	0.01	0.01
Po	Whole body	0.06	0.06
	Liver	0.06	0.01
At	Whole body	1.0	1.0
Fr	Whole body	1.0	1.0
Ra	Whole body	0.3	0.3
	Bone	0.3	0.04
Ac	Whole body	$<10^{-4}$	$<10^{-4}$
Th	Whole body	$<10^{-4}$	$<10^{-4}$
	Bone	$<10^{-4}$	7×10^{-5}
Pa	Whole body	$<10^{-4}$	$<10^{-4}$
U	Whole body	$<10^{-4}$	$<10^{-4}$
	Kidney	$<10^{-4}$	1.1×10^{-5}
Np	Whole body	$<10^{-4}$	$<10^{-4}$
Pu	Whole body	3×10^{-5}	3×10^{-5}
	Bone	3×10^{-5}	2.4×10^{-5}
	Liver	3×10^{-5}	4.5×10^{-6}
Am	Whole body	$<10^{-4}$	$<10^{-4}$
Cm	Whole body	$<10^{-4}$	$<10^{-4}$
Bk	Whole body	3×10^{-5}	3×10^{-5}
Cf	Whole body	3×10^{-5}	3×10^{-5}

Note: The symbol f_1 is the fraction of the ingested material assimilated; a is the fraction of the ingested material that goes to the organ of reference.

This assumes that f_{j+1}, the fraction of the assimilated material which goes to the jth tissue, is independent of the ingestion source. This is reasonable, since the material passing through the gut wall is likely to be of comparable chemical form.

The ingestion equations presented thus far are applicable to short-term exposures, or to chronic exposures over time periods in which the intake parameters remain constant. However, in many chronic ingestion situations, R is time-dependent because one or more of terms r, C, or f_1 are time-dependent. Usually, C is most likely to exhibit time-dependency, but it is also common to observe diurnal or seasonal changes in r. In poikilotherms for instance, r is strongly dependent upon metabolic rate, which in turn is temperature sensitive. The following sorts of time-dependencies in R have been observed.

$$R(t) = \text{constant} \tag{69}$$

$$R(t) = R(o)\, e^{-kt} \tag{70}$$

$$R(t) = R(o)\,[a\, e^{-k_1 t} + b\, e^{-k_2 t}] \tag{71}$$

$$R(t) = R(1)\, t^{-p} \tag{72}$$

$$R(t) = R(eq)\,(1 - e^{-kt}) \tag{73}$$

$$R(t) = R(eq)\,(1 - t^{-p}) \tag{74}$$

$$R(t) = R(o) + a\, t \tag{75}$$

$$R(t) = a \sin(bt + c) + d \tag{76}$$

These equations involve some common exponential, power, linear, and cyclic functions. The application and mathematical manipulation involving intake functions of these types will be illustrated in the chapter subdivision dealing with kinetics of compartment systems.

The practical application of ingestion models requires knowledge or at least estimates of the parameters r, C, and a. Values for C may be estimated by field sampling or by calculation, depending upon the kinds of data available. Assimilation values for different elements have been measured in man and laboratory animals for the express purpose of estimating dose to man (Table 9).[61] Comparable data for other animals are scant, and the usual practice if data on a particular species and nuclide cannot be found is to use the values in Table 9. For more complete data on values for specific organs it is necessary to consult the literature.[61]

The best approach to the estimation of the food consumption rate, r, is to find experimental data which apply to the species of concern for the appropriate set of conditions. Obviously, r is affected by many environmental and physiological variables, so any particular value has a limited range of utility. Lacking specific data, we usually are forced to estimate consumption rates using those principles of animal energetics which have a good theoretical and experimental base. Perhaps the most straightforward approach is the one which considers metabolic rate, maintenance energy requirements, caloric value of foods, and digestible fraction of the energy contained in foods.

It has long been recognized that metabolic rate and thus food energy requirement is closely related to body weight.[62] This bears a fundamental relationship to the ratio of surface area to mass in animals, in that the smaller the mass, the higher is the surface area/mass ratio. The higher this ratio, the greater is the potential for heat loss. Thus, smaller animals tend to compensate for this by maintaining a higher metabolic rate per unit of body weight. For a diverse group of adult homeothermic animals over a wide range of sizes, Kleiber[62] has confirmed the following relationship

$$BMR = 70\, W^{0.75} \tag{77}$$

where BMR = basal metabolic rate in kcal/day and W = live body weight in kilogram. Body weight is thus a good predictor of the basal metabolic rate, but other factors require consideration in the estimation of food intake requirements under field conditions. First, animals must feed themselves, reproduce, defend territories, and conduct other activities which require additional energy expenditures. Secondly, only a portion

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Table 10
CALORIC VALUES OF VARIOUS FOOD MATERIALS

Materal	kcal/g (dry weight)
Terrestrial plants	
Total	4.5
Seeds only	5.2
Algae	4.9
Invertebrates (excl. insects)	3.0
Insects	5.4
Vertebrate tissues	5.6

From Odum, E. P., *Fundamentals of Ecology*, 3rd ed., W. B. Saunders, Philadelphia, 1971. With permission.

of the food energy ingested is actually assimilated and utilized. Finally, natural foods vary in their caloric content, depending on the relative amounts of protein, carbohydrates, and fat. These factors, if known, may now be used to modify the equation for basic metabolic rate to predict the food intake rate (r)

$$r = \frac{a}{dc} 70\, W^{0.75} \tag{78}$$

where r = food intake rate in g/day, a = ratio of active or maintenance metabolic rate to the basal metabolic rate, d = fraction of the energy ingested that is assimilated and oxidized, and c = caloric value of food in kcal/g. The value of a is variable between species and within a species through time in response to biological processes and environmental demands. However, a general "rule of thumb" value of two has been proposed for the expected value of a.[63] The value of d is the amount of energy ingested less the energy lost as feces, urine, and methane divided by the energy ingested. Krebs[64] presents an example for elephants in which d = 0.44 and French et al.[65] cite data for small mammals where d ranges from 0.65 to 0.88. Obviously, the nature of the food consumed and the comparative system of digestion would affect the value of d. In general, one might expect rather high d values for carnivores and lesser values for herbivores. The caloric value of foods is comparatively easy to estimate, since it is known that protein, carbohydrates, and fats contain roughly 5, 4, and 9 kcal/g, respectively. Thus, organic portions of diets may be expected to contain at least 4 and at most 9 kcal/g dry weight. Table 10 gives some caloric values of various natural foods as compiled by Odum.[66]

For larger grazing ruminants, a commonly used predictive equation for dry matter intake is[103]

$$r(\mathrm{kg/day}) = 0.11\, W^{0.75} \tag{79}$$

This equation generally predicts values within a factor of two of measured values. Prosser[67] has compiled a large list of values of the coefficients in Equation 79 for a wide variety of aquatic and terrestrial organisms. This may be of particular use if the caloric values of appropriate foods are known, since the units given by Prosser are either mℓ O_2/g/hr or kcal/kg/day.[67]

French et al.[65] developed a predictive equation for average daily metabolic rate (ADMR) in small mammals weighing W grams.

$$\mathrm{ADMR}\,(\mathrm{kcal/g/day}) = 2.3\, W^{-0.50} \tag{80}$$

Assuming a d value of 0.65 and a c value of 5.0 kcal/g, the prediction of r for small mammals is

$$r(\text{g/day}) = 0.71\ W^{0.50} \qquad (81)$$

where W is in grams-live weight. This equation predicts a dry matter intake of 23% of body weight per day for a 10 g animal and 7% of body weight per day for a 100 g animal. This compares with a predicted intake of 4.2% of body weight per day for a 100 lb sheep and 2.4% of body weight per day for a 1000 lb steer. Spector[68] lists some intake values for a variety of zoo animals. The carnivores consume fresh meat from about 2% of live weight per day for large bears to around 6% of live weight per day for small cats and canids.

Metabolic and food consumption rates for poikilothermic animals are controlled to a dominant extent by ambient temperature. In most poikilotherms, the metabolic rate changes by a factor of 2.5/10°C in the normal range of physiologic activity.[67] Typically, the basal or standard metabolic rate increases continuously with temperature until the lethal temperature is reached. The difference between the active and basal metabolic rate in poikilotherms, which is a measure of work capacity, frequently reaches an optimum at a certain temperature and then declines with further temperature increases. An example of the ambient temperature effect on food consumption was illustrated for rainbow trout in a mountain lake.[69] In midwinter at an ambient water temperature of about 1°C, the consumption rate was estimated as 0.5% of body weight daily. In early summer at a temperature of around 10 to 15°C, food consumption increased dramatically to around 8% of body weight daily. Under optimal temperature conditions, insects consume very large amounts of food in proportion to body weight. For example, Crossley[70] has estimated that a 50 mg insect will consume about 77% of its body weight daily under optimal conditions. No doubt, smaller insects are capable of daily consumption rates well in excess of body weight.

F. Inhalation

Inhalation of airborne particulates and gases represents a major radionuclide transport process, especially in certain situations. Inhaled material, depending on its aerodynamic size and the anatomy of the respiratory system, may be deposited somewhere in the respiratory tract, or exhaled. The fate of the deposited fraction is dependent upon the site of deposition. Aerosol particles larger than a few microns can be expected to deposit largely in the nasal-pharyngeal region. Material deposited in this region is transported rather quickly by ciliary-mucus transport to the esophagus, whereupon the material enters the gastrointestinal tract. In this case, inhaled material is in essence, ingested. Smaller, submicron particles have a good probability of depositing in the pulmonary region of the lung. Such particles are cleared much more slowly, if at all, or they may be absorbed into the body.

Inhalation is of greatest importance when animals are exposed to high air concentrations of radioactive material. High air concentrations may occur near an emission source, or over a dry, dusty area where resuspension of contaminated particles is occurring. In some cases, animals that are in close contact with the soil surface may disturb the surface sufficiently to create an inhalation pathway for radionuclides associated with the surficial dust. Inhalation may be a more critical pathway than ingestion for highly insoluble materials which have been recently deposited in an area. As time post-deposition increases, surficial deposits may weather and become more deeply incorporated in the soil, thus reducing the potential for inhalation. In the case of natural radon gas and radioactive progeny, inhalation should always be considered as a potentially important pathway.

Table 11
LUNG VENTILATION DATA FOR VARIOUS VERTEBRATE SPECIES

Species	Activity level	Breaths/min	Tidal volume (mℓ)
Man			
Newborn	Asleep	43	17
Adult ♂	Resting	12	750
	Light work	17	1670
	Heavy work	21	2030
Adult ♀	Resting	12	339
	Light work	19	860
	Heavy work	30	880
Cat *(Felis catus)*	Resting	26	12
Cow *(Bos taurus)*	Resting	31	2850
Dog	Resting	18	320
Goat	Resting	19	310
Guinea pig *(Cavia cobaya)*	Resting	90	1.8
Hamster *(Mesocricetus auratus)*	Resting	74	0.83
Horse *(Equus caballus)*	Resting	12	9000
Marmot *(Marmota marmota)*	Resting	8	22
	Hibernating	0.68	13
Monkey *(Macaca mulatta)*	Resting	40	21
Mouse *(Mus musculus)*	Resting	163	0.15
Porpoise *(Tursiops truncatus)*	Resting	1.1	9000
Rabbit *(Lepus cuniculus)*	Resting	51	21
Rat *(Rattus norvegicus)*	Resting	67	1.5
Rat *(Sigmodon hispidus)*	Resting	94	0.35
Turtle *(Maleclemys centrata)*	Resting	3.7	14

From Spector, W. S., Ed., *Handbook of Biological Data*, W. B. Saunders, Philadelphia, 1956. With permission.

The first step in evaluating the intake of airborne radionuclides via inhalation is to estimate the rate at which the material enters the respiratory tract. This is simply

$$I = XTB \tag{82}$$

where I = radionuclide inhalation rate in μCi/min, X = air concentration in μCi/ℓ, T = tidal volume in ℓ, and B = breathing rate in number/min. The air concentration would normally be measured or estimated from a dispersion or resuspension calculation, and may be constant or variable in time. The tidal volume and breathing rate are a function of the organism, as well as the activity level of the organism. Table 11 gives some estimated values for breathing rates and tidal volumes in selected vertebrates.

Having an estimate of the radionuclide inhalation rate, the next step is to determine the fraction of inhaled material which is initially deposited in a given region of the respiratory tract. These regions are described as follows:

- The nasopharynx (N-P), beginning with the anterior nares and extending through the pharynx to the level of the larynx or epiglottis
- The tracheobronchial (T-B) region, beginning with the trachea and extending through the bronchial tree down to and including the terminal bronchioles
- The pulmonary (P) region, which includes the functional exchange area of the lung; anatomical structures include the respiratory bronchioles, alveolar ducts,

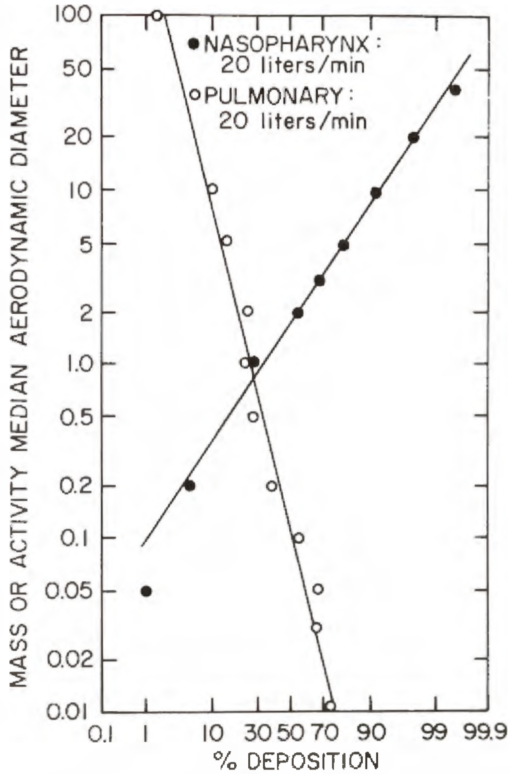

FIGURE 18. Respiratory tract deposition in relation to the activity median aerodynamic diameter (AMAD) of aerosol particles. (Reproduced from *Health Phys.*, Volume 12, Issue 2, page 173, 1966. By permission of the Health Physics Society.) (Diagram from Morgan, K. Z. and Turner, J. E., *Principles of Radiation Protection*, Krieger, Huntington, N.Y., 1973. With permission.)

Based upon experimental work with laboratory animals and humans, the Task Group on Lung Dynamics of the International Commission on Radiological Protection (ICRP) has developed a model of the human lung for the purpose of estimating radiation exposure from inhaled radionuclides.[71] As this model is based on information from humans, dogs, and smaller laboratory mammals, there should be little question as to its applicability to these species. Considering the physiological and anatomical differences among species in general, this model may have rather limited utility throughout the realm of vertebrate animals. However, lacking data germain to a given species, the authors recommend the general use of ICRP lung model for purposes of approximation.

In the ICRP lung model, the deposition fractions for the N-P and P regions are predicted on the basis of the activity median aerodynamic diameters of the aerosol particles (Figure 18). The activity median aerodynamic diameter (AMAD) refers to the median of a distribution of particle radioactivities and to a unit density sphere having the same settling velocity as the particle under consideration. The deposition fraction of the T-B region is less dependent on particle diameter and a constant value of 0.08 is assigned in the lung model. The rate at which inhaled material is deposited in a specific region of the respiratory tract is

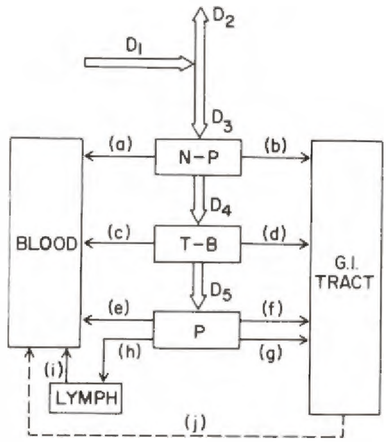

FIGURE 19. Conceptual diagram of the International Commission on Radiological Protection (ICRP) lung model. (Reproduced from *Health Phys.*, Volume 12, Issue 2, page 173, 1966. By permission of the Health Physics Society.) The heavy arrows indicate deposition fractions while the light arrows represent clearance pathways. (Diagram from Morgan, K. Z. and Turner, J. E., *Principles of Radiation Protection*, Krieger, Huntington, N.Y., 1973. With permission.)

Table 12
CLEARANCE PARAMETERS FOR THE PATHWAYS INDICATED IN FIGURE 19

Regions	Pathway	Class D	Class W	Class Y
N-P	a	4 min/0.50	4 min/0.10	4 min/0.01
	b	4 min/0.50	4 min/0.90	4 min/0.99
T-B	c	10 min/0.50	10 min/0.10	10 min/0.01
	d	10 min/0.50	10 min/0.90	10 min/0.99
P	e	30 min/0.80	90 days/0.15	360 days/0.05
	f	n.a.	24 hr/0.40	24 hr/0.40
	g	n.a.	90 days/0.40	360 days/0.40
	h	30 min/0.20	90 days/0.05	360 days/0.15
Lymph	i	30 min/1.00	90 days/1.00	360 days/0.10

Note: Compound classes D, W, and Y are determined from Table 13. The first value is the biological half-time; the second is the pathway fraction. The lymphatic clearance for Class Y compounds indicates that a 10% regional fraction follows a 360-day biological half-time. The remaining 90% is presumed to be permanently retained in the nodes and is subject only to radioactive decay.

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$$R = DI \qquad (83)$$

where R is the rate of deposition in μCi/min, D is the deposition fraction for that region, and I is XTB as defined in Equation 82.

To estimate the quantity of radionuclide in the three regions of the respiratory tract, one must consider the conceptual diagram of the lung model (Figure 19) and retention function for each compartment of the model. This diagram shows the clearance routes and Table 12 indicates the respective clearance half-times and pathway fractions for three classes of materials. The use of clearance half-times and pathway fractions implies that the indicated fractions of the deposited material are each cleared in an exponential manner. The classes of deposited materials (D, W, and Y) are determined on the basis of the chemical characteristics of the radionuclide and expected clearance rates (Table 13). The retention or loss functions L(t) for the model compartments are[72]

N-P: $$L(t) = ae^{-\lambda_a t} + b\,e^{-\lambda_b t} \qquad (84)$$

T-B: $$L(t) = ce^{-\lambda_c t} + de^{-\lambda_d t} \qquad (85)$$

and

P: $$L(t) = ee^{-\lambda_e t} + fe^{-\lambda_f t} + ge^{-\lambda_g t} + he^{-\lambda_h t} \qquad (86)$$

where L(t) = the fraction of a given quantity deposited that remains at the deposition site at time t, a,b,c, etc. = the pathway fractions from Table 12, λ_a, λ_b, λ_c, etc. = effective rate constants for each pathway indicated in Figure 19, and λ_a, λ_b, λ_c, etc. = ln 2/respective biological half-time + ln 2/physical half-life of radionuclide. To estimate the burdens of radioactive material (q, in μCi) in the N-P and P regions for a chronic constant deposition rate (R) in the respective region

N-P: $$q = R_{NP}\int_0^t \left(ae^{-\lambda_a t} + be^{-\lambda_b t}\right) dt \qquad (87)$$

and

P: $$q = R_P\int_0^t \left(ee^{-\lambda_e t} + fe^{-\lambda_f t} + ge^{-\lambda_g t} + he^{-\lambda_h t}\right) dt \qquad (88)$$

In the case of the T-B region, one must account for material passing through it from the P region to the GI tract in addition to the material initially deposited there. This may be expressed as follows:

T-B: $$q = R_{TB}\int_0^t \left(ce^{-\lambda_c t} + de^{-\lambda_d t}\right) dt + R_P\,\tau\left[f\lambda_f\int_0^t e^{-\lambda_f t}\,dt + g\lambda_g\int_0^t e^{-\lambda_g t}\,dt\right] \qquad (89)$$

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Table 13
PULMONARY CLEARANCE CLASSIFICATION OF INORGANIC COMPOUNDS

Class Y—Avid retention: cleared slowly (years)
- Carbides—actinides, lanthanides, Zr, Y, Mn
- Sulfides—none
- Sulfates—none
- Carbonates—none
- Phosphates—none
- Oxides and hydroxides—lanthanides, actinides Groups 8 (V and VI), 1b, 2b (IV and V), 3b except Sc^{3+}, and 6b
- Halides—lanthanide fluorides
- Nitrates—none

Class W—Moderate retention: intermediate clearance rates (weeks)
- Carbides—Cations of all Class W hydroxides except those listed as Class Y carbides.
- Sulfides—Groups 2a (V + VI), 4a (IV-VI), 5a (IV-VI), 1b, 2b and 6b (V + VI)
- Sulfates—Groups 2a (IV-VII), and 5a (IV-VI)
- Carbonates—lanthanides, Bi^{3+} and Group 2a (IV-VII)
- Phosphates—Zn^{2+}, Sn^{4+}, Mg^{2+}, Fe^{3+}, Bi^{3+}, and lanthanides
- Oxides and hydroxides—Groups 2a (II-VII), 3a (III-VI), 4a (III-VI), 5a (IV-VI), 6a (IV-VI), 8, 2b (VI), 4b, 5b, and 7b Sc^{3+}
- Halides—lanthanides (except fluorides), Groups 2a, 3a (III-VI), 4a (IV-VI), 5a (IV-VI), 8, 1b, 2b, 3b (IV-V), 4b, 5b, 6b, and 7b
- Nitrates—all cations whose hydroxides are Class Y and W

Class D—Minimal retention: rapid clearance (days)
- Carbides—see hydroxides
- Sulfides—all except Class W
- Sulfates—all except Class W
- Carbonates—all except Class W
- Phosphates—all except Class W
- Oxides and Hydroxides—Groups 1a, 3a (II), 4a (II), 5a (II, III), and 6a (III)
- Halides—Groups 1a and 7a
- Nitrates—all except Class W
- Noble Gases—Group 0

The periodic table of the elements on page 50 is used with the foregoing classification

Note: Where reference is made from one chemical form to another, it implies that an in vivo conversion occurs, e.g., hydrolysis reaction.

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where τ is the mean residence time in the T-B region of material passing from the pulmonary region to the GI tract. In the ICRP lung model, τ is taken as 1 hr. The derivation of and rational for Equations 84 through 89 may not be clear to the reader at this point. However, this will be covered in the subsequent sections on retention and kinetics.

The lung model may be coupled to the ingestion model by adding to the ingesta that material which is cleared from the respiratory tract by pathways b, d, f, and g (Figure 19). The rate of GI tract entry from the respiratory tract is the sum of the products of the regional inventories and respective rate constants for the appropriate pathways.

G. Retention and Loss

The problem of retention and loss must be considered if one is to predict the quantity of a radioactive substance in a compartment or system of compartments. It is intuitive that a compartment, say a mouse for example, will display a certain retention pattern for a radionuclide following an acute dose. The retention pattern will be governed by the rate at which the material is lost from the body. The rate of loss will be dependent

Table 13 (continued)
PULMONARY CLEARANCE CLASSIFICATION OF INORGANIC COMPOUNDS

	Group																		
Period	1a	2a	3b	4b	5b	6b	7b	8			1b	2b	3a	4a	5a	6a	7a	0
I	H																	He
II	Li	Be											B	C	N	O	F	Ne
III	Na	Mg											Al	Si	P	S	Cl	Ar
IV	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
V	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
VI	Cs	Ba	La*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
VII	Fr	Ra	Ac†															

* Lanthanides	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
† Actinides	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lw

upon the site of deposition, processes of elimination, metabolic rate, chemical form of the radionuclide, and other factors. The unitless retention or loss function, L(t), following an acute dose is given by

$$L(t) = \frac{q(t)}{q(o)} \tag{90}$$

where q(t) = the quantity of radionuclide present at (t) and q(o) = the initial quantity present (the dose). Ordinarily, the function q(t) is most conveniently determined by whole-body counting or sampling through time.

Perhaps less intuitive, is the fact that the quantity of radionuclide in a compartment through time under conditions of chronic intake is highly dependent upon the loss function, as well as the rate of intake. Thus in any dynamic system in which materials enter and leave, the material content of the system bears fundamental relationships to the rates of intake and loss. Since loss from any compartment is a fundamental transport process, it is appropriate that it be discussed at this point.

The mechanisms of radionuclide loss are many, and highly dependent upon the nature of the compartment and the properties of the radioactive material. Certainly, physical decay is of importance for relatively short-lived radionuclides, irrespective of the compartment. Animals lose radionuclides by mechanisms such as excretion, exhalation, secretion, and molting. If an animal population is considered a compartment, then mortality of individuals also results in loss of material from the compartment. If material is surficially attached to the animal's body surface, then a variety of physical mechanisms may cause its removal. This highlights the importance of deposition site on the mechanisms and rates of loss. Plants lose radionuclides through leaching, surface weathering, leaf fall, secretions, and of course, mortality and consumption in the case of populations. Soil and detritus as a compartment may exhibit loss through leach-

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ing, desorption, transport of the compartmental material per se, and uptake by plants or animals.

The complex array of factors which determine rates of loss are manifest in the loss function, L(t). The relation between the likely time-dependent rate of loss, $R_\ell(t)$, in μCi/time, and L(t) is

$$L(t) = \frac{q(o) - \int_o^t R_\ell(t)dt}{q(o)} \tag{91}$$

since $q(t) = q(o) -$ the amount lost in time (t) and $q(t) = q(o) - \int_o^t R_\ell(t)dt$. The loss function may be determined in this manner if the time-dependent rate of loss can be measured. For example, if $R_\ell(t) = k\,q(o)e^{-kt}$, then

$$L(t) = \frac{q(o) - \int_o^t \left[kq(o)e^{-kt}\right] dt}{q(o)}$$

$$= e^{-kt}$$

In this case, k is a constant, having the units of time $^{-1}$. The properties of k will next be examined in the light of the simplest compartment model, namely that which exhibits first order loss.

A single compartment which obeys first-order kinetics may be conceptualized as

$$\boxed{q} \xrightarrow{k}$$

and formulated mathematically as

$$\frac{dq}{dt} = -kq \tag{92}$$

This equation says that the instantaneous rate of change in the quantity q is proportional to q, k being the constant of proportionality. Thus, k is the fraction of q that is lost from the compartment per unit time, providing one is considering very small time intervals. The term k is frequently and most appropriately called a "rate constant". It was shown in Volume I, Chapter 3 that the process of radioactive decay follows Equation 92. Many other processes involving the loss of radioactive material also exhibit this behavior. It is easily shown (see Volume I, Chapter 3) that integration of Equation 92 yields

$$q(t) = q(o)e^{-kt} \tag{93}$$

when one sets $q = q(o)$ at $t = 0$. It may also be shown that k is fundamentally related to the term called the "half time" ($T_{1/2}$) by

$$k = \frac{\ln 2}{T_{1/2}} \tag{94}$$

where $T_{1/2}$ = the time required for q to decrease by a factor of 2. Also, k is related to the mean lifetime (τ) of a parcel of material in the compartment by

$$k = \frac{1}{\tau} \tag{95}$$

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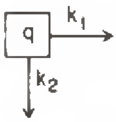
Thus, τ and $T_{1/2}$ are related by

$$\frac{\ln 2}{T_{1/2}} = \frac{1}{\tau} \tag{96}$$

$$\tau = \frac{T_{1/2}}{\ln 2}$$

$$= 1.44\ T_{1/2}$$

A commonly encountered variation to the first-order model the authors have just described is one that exhibits more than one loss pathway. For instance, one sees many examples of the system



where k_1 may represent and quantify loss through a biological process and k_2 represents loss through physical decay of the radionuclide. In this situation,

$$\frac{dq}{dt} = -(k_1 + k_2)q$$

and

$$q = q(o)e^{-(k_1 + k_2)t} \tag{97}$$

Frequently, one replaces $k_1 + k_2$ by k_{eff}, the effective loss rate constant

$$k_{eff} = k_1 + k_2 \tag{98}$$

This relates to the term "effective half-time" (T_{eff}), where

$$T_{eff} = \frac{\ln 2}{k_{eff}} \tag{99}$$

Also

$$T_{eff} = \frac{T_1\ T_2}{T_1 + T_2} \tag{100}$$

where $T_1 = \ln 2/k_1$ and $T_2 = \ln 2/k_2$.

So long as one is dealing with a common compartment, there may be any number of first-order rate constants operating on it which may be summed to obtain an effective rate constant

$$k_{eff} = \sum_{i=1}^{n} k_i \tag{101}$$

A plot of ln q vs. t for any of the systems just described will yield a straight line (Figure 20). Note however, that the number of exit pathways from a single compartment cannot be inferred from a data plot. One must have additional information to make such a determination.

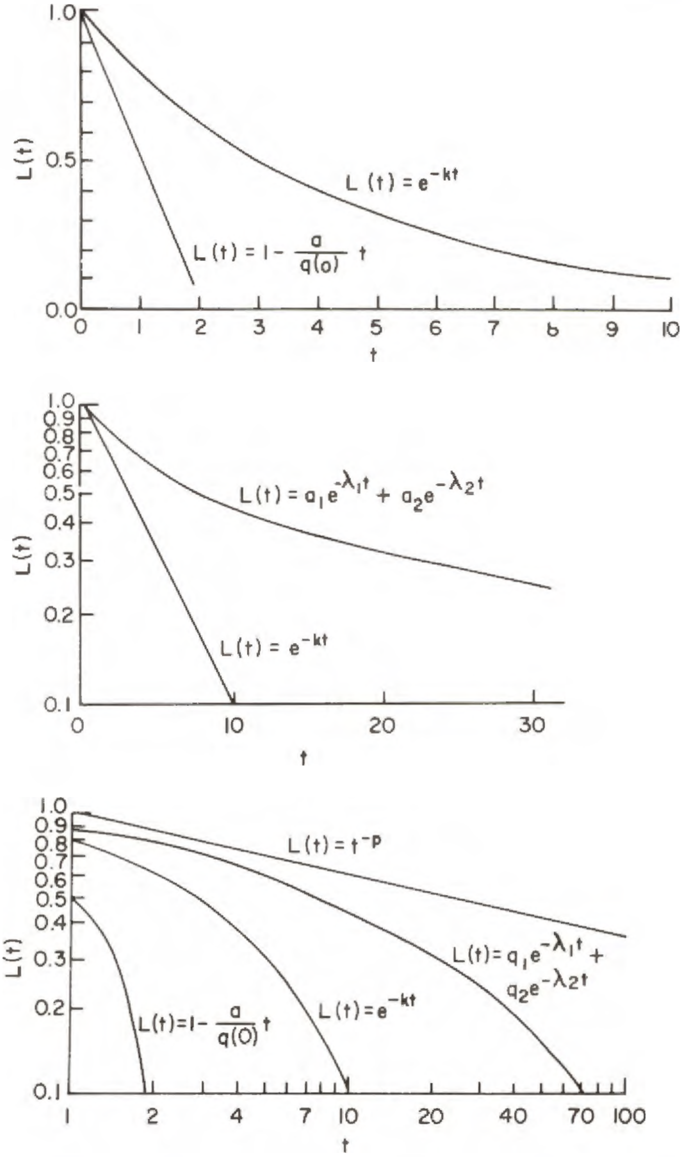


FIGURE 20. Plots of linear, exponential, and power function retention curves.

Another common type of retention function is the multicomponent exponential form

$$L(t) = \sum_{i=1}^{n} a_i e^{-\lambda_i t} \tag{102}$$

Examples of this sort of function were presented for the lung model earlier in this chapter. Note that the authors have used the symbol λ, rather than k. The reason for this is that λ values, although having the same dimensional units as k values (t^{-1}), may not truly represent rate constant values. More often than not, the λ values are simply derived parameters that are related, but not necessarily equal to the fundamental rate constants of a compartment system. For example, the system

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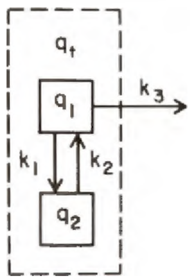
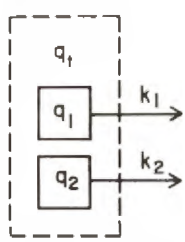


yields a retention function of the form (Figure 20)

$$L(t) = \frac{q_t(t)}{q_t(o)} = a_1 e^{-\lambda_1 t} + a_2 e^{-\lambda_2 t} \tag{103}$$

where $q_t = q_1 + q_2$. In this case, the parameters a_1, a_2, λ_1, and λ_2 are related mathematically to k_1, k_2, and k_3. Hence, it may be possible to estimate the rate constants from the measured parameters, or vice versa. The two-compartment system above is sometimes a useful physiological analogue for certain radionuclides in animals.[73] While in reality, an animal is a complex system composed of many interconnected compartments, the researcher is usually well advised to use the simplest possible model which adequately describes behavior of the system.

Other systems could also yield a retention function of the same form as Equation 103. For example, the system below would yield such a function.



In this case, the rate constants k_1 and k_2 would be identical to λ_1 and λ_2, respectively. In addition, a_1 would correspond to $q_1(o)$ and a_2 to $q_2(o)$. Note that the subcompartments of this system are not interconnected and thus behave as two isolated single compartments. An example of this type of system might be a plant in which q_1 represents internally deposited material and q_2 represents surficial contamination. The total radionuclide content is q_t.

As the number of subcompartments in a system coupled by first order rate processes is increased, it becomes more likely that the retention function can be best described by larger numbers of exponential terms. However, the number of exponential terms that one can resolve in the analysis of a retention function is not necessarily directly related to the number of subcompartments. The intercompartmental linkages, exit pathways, and the relative values of the rate constants will all influence the shape of the retention function. In many cases, retention data may be described reasonably well by several models, say two, three, or four component exponentials, or even a power function. The determination of the best-fitting model becomes an exercise in the statistics of curve-fitting.

The power function sometimes provides a reasonable description of multicomponent exponential systems. For example, the decay of a mixture of fission products has been

observed to roughly follow a $t^{-1.2}$ relationship (Volume I, Chapter 4, Equation 2), even though the decay of the individual component radionuclides is strictly exponential. Another example is the retention of many radionuclides in bone. Since bone tissue is not a true compartment in the sense that mixing and exchange is limited to varying degrees depending on vascularity and other factors, one would not expect single compartment behavior. Rather, one can expect to see a comparatively rapid loss of material deposited near the bone-blood surface, and progressively slower loss for deposits deeper within the bone matrix.

The basic power function for retention is

$$L(t) = t^{-P} \tag{104}$$

where t must be expressed in terms of multiples of some unit reference time, because L(t) is undefined if one set t = 0. In the power function case,

$$L(t) = \frac{q(t)}{q(1)} \tag{105}$$

where q(1) is the radionuclide content at unit reference time. The power function yields a straight line on a log-log plot (Figure 20), thus a plot of retention data on semilog and log-log paper can give a good clue as to the appropriate model.

An interesting view of the power function for radionuclide retention was presented by Raabe.[74] The case where the rate constant describing loss was itself a function of time was given

$$\boxed{q} \xrightarrow{k(t)}$$

$$k(t) = \frac{k}{t} \tag{106}$$

For this system,

$$\frac{dq}{dt} = -\left(\frac{k}{t}\right) q \tag{107}$$

Solving this differential equation

$$\int \frac{dq}{q} = -k \int \frac{dt}{t}$$

$$\ln q = -k \ln t + C$$

where C is the integration constant. If q = q(1) at t = t(1), then $C = \ln [q(1)t(1)^k]$. Thus,

$$\begin{aligned} \ln q &= -k \ln t + \ln [q(1)t(1)^k] \\ q &= [q(1)t(1)^k]\, t^{-k} \end{aligned} \tag{108}$$

which is of the form

$$q = a\, t^{-P}$$

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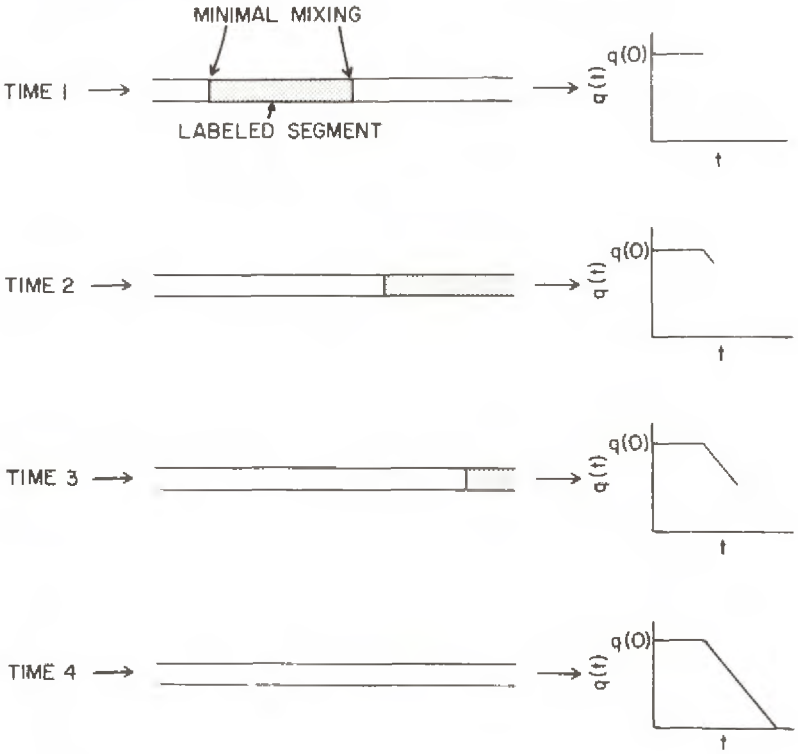

FIGURE 21. Conceptual diagram and retention plots for a narrow tube of constant flow containing a segment labeled with a radioactive substance.

It is not uncommon to find cases where the loss rate constant becomes smaller with time. For instance, in animals that show a decreasing metabolic rate with time due to growth, age or other factors, the biological half time of many elements can be expected to increase (thus decreasing the value of k).[75] However, k(t) will not necessarily equal k/t as in the example above.

The other basic type of retention function under consideration here is the linear one

$$L(t) = \frac{q(o) - a\,t}{q\,(o)}$$

$$= 1 - \frac{a}{q\,(o)}\,t \tag{109}$$

where a is a constant that describes the rate of loss in μCi/unit time. Note that this function is only valid where the quantity $a/q(o)\ t \leq 1$, because q(t) and hence, L(t) cannot be negative. Few biological or physical systems exhibit this type of loss and it thus has fewer applications than the exponential and power function models. However, one system that may exhibit a linear loss function is a narrow tube through which materials are passing at a constant rate (Figure 21). If a portion of the material in the tube is uniformly labeled with a radioactive substance and longitudinal mixing is negligible, the loss function may be linear. Material in the gastrointestinal tract may exhibit such behavior in certain cases.

The necessity to determine appropriate retention functions for systems which one wishes to model will become increasingly evident in subsequent sections of this chapter. The usual practice is to dose the system of interest and measure the radio-

nuclide content through time. The next problem is to determine a reasonable mathematical expression which best describes the observed data. Some simple techniques for doing this are described in a subsequent chapter section entitled, "Analysis of Experimental Data."

Considerable data are available on biological half-times of radionuclides in a variety of species. Table 14 lists a few values for certain animals. These data were largely compiled by Kitchings and colleagues at Oak Ridge National Laboratory, Oak Ridge, Tenn., and their paper should be consulted for reference to the original works.[76] A few other values, based mostly on work by graduate students at Colorado State University, Fort Collins, and the senior author are also given. Since biological half-times are given, it is assumed that exponential retention models are applicable. Animals exhibit reasonably consistent relationships between the long component retention half-time, T_2 in days, and body weight, W in grams. Kitchings and colleagues[76] and Reichle and co-workers[81] have summarized some of these empirical relationships as follows:

Cesium

$$T_2 = 3.5\, W^{0.24} \tag{110}$$

Strontium

$$T_2 = 107\, W^{0.26} \tag{111}$$

Iodine

$$T_2 = 6.8\, W^{0.13} \tag{112}$$

Cobalt

$$T_2 = 2.6\, W^{0.24} \tag{113}$$

Tritium

$$T_2 = 0.82\, W^{0.55} \tag{114}$$

It is cautioned that these statistical relationships are based on very limited data from a few species. Also, factors other than body weight are not considered. Therefore, general applicability of these equations is questionable. Specific data would be much more credible if available.

Retention data for plants are much more scarce than for animals; however, some pertinent work has been done. As with animals, most retention data for plants may be fit with the exponential model. A few measured retention half-times for plants are listed in Table 15. These studies involved surficial application of the material and thus represent primarily surface retention. Retention of material incorporated into tissues following root uptake could be expected to be greater, but pertinent data were not found. Although the literature suggests substantial variation in retention half-times by plants, the U.S. Nuclear Regulatory Commission suggests generic use of a half-time value of 14 days when specific data are not available.[88] Note that extremely long-lived, slow growing plants such as lichens exhibit very long retention half-times, and this is a principal reason for the comparatively high concentrations of fallout radionuclides in terrestrial ecosystems of the arctic.

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Table 14 (continued)
BIOLOGICAL HALF-TIME DATA[a] FOR SELECTED RADIONUCLIDES AND ANIMAL SPECIES

Nuclides	Species (wt), Organ	T_1	a_1	T_2	a_2	Notes	Ref.
	Kangaroo rat (90 g)						
	Whole body			12 day			76
	Lab rabbit (3 kg)						
	Whole body			3.9 day			76
	Dog (10 kg)						
	Whole body			5.1 day			76
	Horse (400 kg)						
	Whole body			8.4 day			76
^{32}P	Grasshoppers (344 mg)						
	Whole body	9.8 hr	0.4	14 day	0.6	Parameters temperature, sex, species dependent	80

[a] T_1 and T_2 are biological half-times for short and long components, respectively, in days or hours; a_1 and a_2 are the time zero intercepts of the short and long components, respectively, expressed as a fraction of the initial organ burden.

[b] Single component exponential retention is assumed for tritium.

Adapted with additions from Kitchings, T., DiGregorio, D., and Van Voris, P., *Radioecology and Energy Resources*, Cushing, C. E. et al., Eds., Dowden, Hutchinson & Ross, Stroudsburg, Pa., 1976, 304.

Table 15
RETENTION HALF-TIMES MEASURED FOR VARIOUS RADIONUCLIDES AND MATERIALS APPLIED SURFICIALLY TO VEGETATION

Material applied	Species	Retention half-time (days)	Notes	Ref.
^{137}Cs-tagged particles	Fescue grass	30		82
Iodine (I_2)	Grass	6.9		83
	Clover	5		83
^{134}Cs submicron[a] aerosol	*Sitanion hystrix*	8.7	Spring value for long-component	32
		41	Summer value for long-component	32
	Artemisia tridentata	17	Spring value for long-component	32
		27	Summer value for long-component	32
^{144}Ce submicron[a] aerosol	*Sitanion hystrix*	8.7	Spring value for long-component	32
		27	Summer value for long-component	32
	Artemisia tridentata	12	Spring value for long-component	32
		22	Summer value for long-component	32
Various radionuclides	U.K. pastures	14	Value of 9 days better for rapidly growing crops	84
88—175 μm particles	Varied (trees, crops)	1.8	Mean value 0—1.5 days post-contamination	85
	Varied (trees, crops)	9.2	Mean value 1.5—14 days post-contamination	85
		21.3	Mean value 14—33 days post-contamination	85
88—175 μm; 175—350 μm particles	Various crops	6—14	Initial values of 1 day observed, as well as some final half-times approaching ∞	86
^{134}Cs, ^{137}Cs	Arctic lichens	2500 to >3650	Field studies with established plots	87

[a] In these studies, a short-component half-time of 1 to 2 days was observed for both nuclides.

H. Empirical Concentration Ratios

The general intent of this chapter is to provide a reasonably realistic, process-oriented, yet practical basis for the quantitative prediction of radionuclide transport in ecosystems. In cases where processes of uptake and loss may be quantified, this intent can be satisfied in a reasonable way. However, there exist cases where processes of uptake and loss are not sufficiently understood to make intelligent predictions of radionuclide concentrations. In such cases, the authors often resort to direct measurements of radionuclide levels in the compartment of interest and also in some base compartment of the ecosystem, such as soil, water, or food. The ratio of concentrations, called such things as "concentration factor", "bioaccumulation factor", and the preferred term, "concentration ratio" (CR) is simply

$$CR = \frac{\mu Ci/g \text{ in compartment of interest}}{\mu Ci/g \text{ in base or reference compartment}} \tag{115}$$

While CR values are strictly empirical and provide no fundamental understanding of processes, they are of some utility, particularly if measured in the system for which predictions are to be made.

A number of weaknesses in the concentration ratio concept are evident and these are worth pointing out. First, there is usually no sure way of knowing that the compartment of interest is in equilibrium with the reference compartment, unless time-series data are available. Equilibrium means that rate of intake is equal to rate of loss

and thus the compartment content is constant in time. Equilibrium is the only condition under which the CR value is constant and thus predictable. Compartments which have short effective half times reach equilibrium rapidly and the equilibrium question may not be troublesome.

A second problem with concentration ratios is that they are influenced by many factors associated with the properties of the radionuclide, the organism, and the ecosystem. As a result, individual measurements display a great deal of variability. Thus for example, a measured CR for ^{137}Cs in rainbow trout should not be universally applied to all situations involving cesium and rainbow trout. To do so without considerable ancillary information could lead to error by as much as one or even perhaps two orders of magnitude.

A common problem with the interpretation of concentration ratios in aquatic systems is the expression of radionuclide concentration in water, the usual reference compartment. For instance, the amount of radioactivity in a gram of water as sampled may be much greater than the amount in a gram of water that has been filtered to remove seston (suspended particulate matter). Seston usually exhibits very high CR values and a small amount of this material suspended in water may contain most of the radioactivity in a water sample. Thus, the CR may be highly dependent on whether or not the water was filtered prior to measurement. Much of the open literature on CR values in aquatic systems fails to indicate whether or not the water was filtered. For the sake of uniformity, the authors encourage investigators to filter the seston from water samples prior to assay. Millipore® 0.45 μm or equivalent filters are normally used.

Due in part to the complexity of uptake and loss mechanisms, there are few data on the kinetic processes of radionuclide transfer from soil to plants. One complicating factor for example, is the growth of vegetation. This produces a nonsteady state system and uptake and loss parameters which change with time. Thus, soil-plant relationships for radionuclides are most commonly expressed as a concentration ratio, with soil as the reference compartment. Another problem with the CR concept is raised where soil is the reference compartment and the distribution of radioactivity with depth is nonuniform. This brings up the question of how to sample the soil. Probably the most common practice is to measure the average radionuclide concentration in the soil that is within the root zone of the plant. However, many papers on the subject do not indicate the method and rationale for soil sampling.

The U.S. Nuclear Regulatory Commission has published a list of typical plant/soil concentration ratios for use in evaluating transport of radionuclides to man.[88] This list is given in Table 16. As with other CR data, the authors recommend the use of data specific to the vegetation and soil types of concern when available. Certainly, many cases may be found where observed CR values differ substantially from those listed in Table 16. Note that Table 16 gives CR values by elements rather than by specific radionuclides. The assumption implicit in the use of element CR values is that radionuclides of each element will reach equivalent steady state values. Another way of expressing this concept is that at equilibrium

$$\frac{\mu\text{Ci of radioisotope/g organism}}{\mu\text{Ci of radioisotope/g reference compartment}} = \frac{\text{g stable element/g organism}}{\text{g stable element/g reference compartment}} \qquad (116)$$

This idea has been discussed thoroughly in the literature.[81]

Table 16
PLANT/SOIL CONCENTRATION RATIOS (CR) FOR VARIOUS ELEMENTS AS UTILIZED BY THE U.S. NUCLEAR REGULATORY COMMISSION

Element	CR*	Element	CR
H	4.8×10^{0}	Mo	1.2×10^{-1}
C	5.5×10^{0}	Tc	2.5×10^{-1}
Na	5.2×10^{-2}	Ru	5.0×10^{-2}
P	1.1×10^{0}	Rh	1.3×10^{1}
Cr	2.5×10^{-4}	Ag	1.5×10^{-1}
Mn	2.9×10^{-2}	Te	1.3×10^{0}
Fe	6.6×10^{-4}	I	2.0×10^{-2}
Co	9.4×10^{-3}	Cs	1.0×10^{-2}
Ni	1.9×10^{-2}	Ba	5.0×10^{-3}
Cu	1.2×10^{-1}	La	2.5×10^{-3}
Zn	4.0×10^{-1}	Ce	2.5×10^{-3}
Rb	1.3×10^{-1}	Pr	2.5×10^{-3}
Sr	1.7×10^{-2}	Nd	2.4×10^{-3}
Y	2.6×10^{-3}	W	1.8×10^{-2}
Zr	1.7×10^{-4}	Np	2.5×10^{-3}
Nb	9.4×10^{-3}		

* CR = pCi/kg vegetation÷pCi/kg soil.

From the U.S. Nuclear Regulatory Commission, Regulatory Guide 1.109 (Rev. 1), Washington, D.C., 1977.

Several elements of considerable interest are not listed in Table 16, including radium and important actinides such as U, Th, Pu, and Am. Few data are available for Ra, but based on limited work and comparison to chemically similar Ca and Sr, CR values between 0.1 and 0.01 would appear reasonable. Uranium shows measurable uptake, particularly in certain plant species. However, CR values for U range over three orders of magnitude from 10^{-4} to over 10^{-1}. Thorium is very poorly absorbed by plants and CR values $< 10^{-4}$ can be expected. Plutonium is also poorly absorbed, pot studies yielding CR values in the range of 10^{-8} to 10^{-3}, with a value of 10^{-4} useful as a rule of thumb.[89] Plant/soil CR values for Pu seem particularly dependent on chemical form.[89] In comparable situations Am exhibits CR values perhaps 100-fold higher than Pu.[89] It is important to note that the data just cited, including that in Table 16, primarily reflect root uptake. Aerial deposition of material on vegetation must be considered separately because this mechanism can be much more significant then root uptake, particularly in the more arid situations.

Reichle and colleagues[81] compiled a review of animal/plant concentration ratios for several elements in terrestrial ecosystems (Table 17). Presumably, the values represent mean whole body concentrations in the animals. Obviously, the CR values would vary considerably for different types of tissues. Another uncertainty, which typifies yet another necessary qualification in using concentration ratios for predictive purposes, is whether the values in Table 17 are based on wet or dry weights in both the animals and the plant food base. To clarify this, one would need to trace each value to its original source in the literature. Comparison of CR values across the elements listed is indicative of their relative mobility in food chains.

A fairly comprehensive list of elemental concentration ratios for freshwater and ma-

Table 17
ANIMAL/PLANT CONCENTRATION RATIOS FOR SELECTED ELEMENTS IN TERRESTRIAL ECOSYSTEMS

	Invertebrates			Mammals		
Element	Saprivores	Herbivores	Carnivores	Herbivores	Omnivores	Carnivores
Ca	0.1—18	0.1	0.1			
Sr		0.1	0.1	0.5—4.5		
K	3.5	3.0	2.0			
Cs	0.2	0.3—0.5	0.1—0.5	0.3—2.0	1.2—2.0	3.8—7.0
Na	17	21	27			
Co		0.4	0.5	0.3		
Ru		0.4	1.2	0.4		
Fe				0.8	0.2	
H	0.6			0.6		
P	11	17	18			
Ra				0.01		
I				0.5	0.2	0.1

From Reichle, D. E., Dunaway, P. B., and Nelson, D. J., *Nucl. Saf.*, 11(1), 43, 1970.

rine organisms is utilized by the U.S. Nuclear Regulatory Commission when site-specific information is not available.[88] This list is reproduced in Table 18. Reference to the original literature is recommended prior to application of these values for predictive purposes. A thorough treatise on concentration ratios for radionuclides in freshwater and marine systems was prepared by our Russian colleague, Polikarpov.[90] This volume should be consulted for most serious attempts to estimate radionuclide concentrations in aquatic organisms on the basis of concentrations in water.

This section was prepared to illustrate some of the concepts and literature available on concentration ratios. It is by no means comprehensive or complete and a great deal of literature exists on the subject that the authors have not cited. The point, alluded to numerous times in this volume, that accurate, credible prediction demands site- and circumstance-specific data, is emphasized once again.

III. B. KINETICS OF COMPARTMENT SYSTEMS

In this section the authors present a treatment of those fundamental concepts of tracer kinetics which have direct application to the prediction of radionuclide transport and accumulation. The goal is to develop mathematical equations which employ intake and loss parameters to estimate the quantities of radionuclides in biological or ecological compartments through time. Single, as well as coupled multicompartment systems are treated to the extent that reasonable analytical solutions exist. Coupled systems of four or more compartments usually become so cumbersome, mathematically, that nu-

Table 18
CONCENTRATION RATIOS FOR AQUATIC ORGANISMS AS UTILIZED BY THE U.S. NUCLEAR REGULATORY COMMISSION IN THE ABSENCE OF SITE-SPECIFIC DATA

	Freshwater		Saltwater	
Element	Fish	Invertebrate	Fish	Invertebrate
H	9.0E-01	9.0E-01	9.0E-01	9.3E-01
C	4.6E 03	9.1E 03	1.8E 03	1.4E 03
Na	1.0E 02	2.0E 02	6.7E-02	1.9E-01
P	1.0E 05	2.0E 04	2.9E 04	3.0E 04
Cr	2.0E 02	2.0E 03	4.0E 02	2.0E 03
Mn	4.0E 02	9.0E 04	5.5E 02	4.0E 02
Fe	1.0E 02	3.2E 03	3.0E 03	2.0E 04
Co	5.0E 01	2.0E 02	1.0E 02	1.0E 03
Ni	1.0E 02	1.0E 02	1.0E 02	2.5E 02
Cu	5.0E 01	4.0E 02	6.7E 02	1.7E 03
Zn	2.0E 03	1.0E 04	2.0E 03	5.0E 04
Br	4.2E 02	3.3E 02	1.5E-02	3.1E 00
Rb	2.0E 03	1.0E 03	8.3E 00	1.7E 01
Sr	3.0E 01	1.0E 02	2.0E 00	2.0E 01
Y	2.5E 01	1.0E 03	2.5E 01	1.0E 03
Zr	3.3E 00	6.7E 00	2.0E 02	8.0E 01
Nb	3.0E 04	1.0E 02	3.0E 04	1.0E 02
Mo	1.0E 01	1.0E 01	1.0E 01	1.0E 01
Tc	1.5E 01	5.0E 00	1.0E 01	5.0E 01
Ru	1.0E 01	3.0E 02	3.0E 00	1.0E 03
Rh	1.0E 01	3.0E 02	1.0E 01	2.0E 03
Te	4.0E 02	6.1E 03	1.0E 01	1.0E 02
I	1.5E 01	5.0E 00	1.0E 01	5.0E 01
Cs	2.0E 03	1.0E 03	4.0E 01	2.5E 01
Ba	4.0E 00	2.0E 02	1.0E 01	1.0E 02
La	2.5E 01	1.0E 03	2.5E 01	1.0E 03
Ce	1.0E 00	1.0E 03	1.0E 01	6.0E 02
Pr	2.5E 01	1.0E 03	2.5E 01	1.0E 03
Nd	2.5E 01	1.0E 03	2.5E 01	1.0E 03
W	1.2E 03	1.0E 01	3.0E 01	3.0E 01
Np	1.0E 01	4.0E 02	1.0E 01	1.0E 01

Note: Units are pCi/kg ÷ pCi/ℓ = ℓ/kg. In above notation for example, 9.0E-01 = 9.0×10^{-1}; 4.6E 03 = 4.6×10^{3}, etc.

From the U.S. Nuclear Regulatory Commission, Regulatory Guide 1.109 (Rev. 1), Washington, D.C., 1977.

merical approximation solutions by computer are required. The authors comment on such systems and methods of their analysis, but do not treat them in detail. A clear treatment of tracer kinetics requires a good understanding of the commonly used terms and their meaning, so the authors shall begin there. There are a number of excellent texts on tracer kinetics available.[91-94] Our purpose is to apply well-known principles of tracer kinetics to the problem of radionuclide transport in ecological systems.

A. Terminology

1. System

A system may be considered an aggregate of parts which interact in such a way as to lend properties to the whole which supercede the sum of properties of the parts. A

system may be visualized at the cellular, organismic, or ecological levels in the biological realm. Examples of other recognized systems include industrial, social, mechanical, electrical, and hydrologic. In this book, the authors are mainly concerned with ecological and sometimes physiological systems. Necessary components of ecological systems include air, water, soil, green plants, consumer organisms, organic detritus, and associated decomposer organisms. Our concern is the transfer of radionuclides between such components and their accumulation within each component.

2. Compartment

A compartment can be thought of as a space, usually having defined boundaries, within which materials are free to move and mix, thereby achieving reasonably homogeneous concentrations throughout. A compartment that can exchange materials with the space outside is considered an "open" compartment. Otherwise, the compartment is said to be "closed". A compartment which receives material from the outside, but does not release it is termed an "accumulation compartment", or "sink". In practice, the compartment is often more a concept than a reality because few biological or ecological examples obey the strict definition of a compartment. In an open compartment space in which materials mix at a rate that is rapid with respect to the rate at which the material enters and exits, then one usually treats that space as a compartment. For practical reasons, one often treats an aggregation of compartments or systems per se as a single compartment. Judgment and rationale, therefore, come into play in the development of compartment models.

3. Steady State

A compartment is said to be in steady state when basic elements or other substances involved in normal processes are entering it at the same rate as that by which they are leaving. In this condition, the content of material within the compartment is constant in time, even though such material is being continually replaced. A compartment in steady state can be expected to have physical dimensions and input and loss functions which are essentially constant through time. In nature, few compartments are in perfect steady state because of dynamic processes such as growth and ecological change. However, if the compartment of interest does not change significantly during the time frame of interest, then steady state is assumed because the mathematics of steady-state systems are much more manageable than nonsteady state systems.

4. Tracee (Mother Substance)

The kinetics of a compartment system are basically governed by the flow of a fluid medium and sometimes also by the behavior of a natural substance within the fluid medium. A common example of the basic fluid medium is water and particular elements, compounds or solid aggregates may represent the natural substance that will control the flow of a tracer or pollutant which may be introduced into the system. The fluid medium or the natural substance which dominates the flow of the tracer of interest is called the "tracee" or "mother substance". When a compartment is evaluated to determine whether or not it is in steady state, it is the content and flow of tracee that must be examined.

5. Tracer (Pollutant)

Radionuclides introduced into ecosystems are normally present in atom concentrations which are very low in comparison to atom concentrations of similar, normally present substances. Thus, their behavior is likely governed by that of these similar substances (the tracee), rather than by their own mass characteristics. When this is the case, one treats the radionuclide as a "tracer". The tracer "traces" or "mimmicks"

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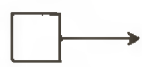
the normal movements of the tracee. Of course, the specific tracee that is traced is dependent upon the physical and chemical properties of the tracer. Long-lived, low-specific activity radionuclides, or those radionuclides which are chemically or physically dissimilar to normal substances which flow through ecological and physiological systems may not have suitable tracees, and therefore, it is not appropriate to call such materials tracers.

6. Transport Pathway

This term refers to a route by which material passes into or from a particular compartment, or a route of passage between two specific compartments. A transport pathway must represent and involve specific structures and/or processes. Some common examples of transport pathways include deposition, resuspension, sorption, desorption, ingestion, excretion, molting, secretion, and decomposition.

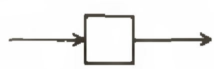
7. Conceptual Models

Conceptual models of compartment systems as covered in this chapter are symbolic representations of the compartments comprising the systems of interest, with indication of the transport pathways. For example, a single compartment exhibiting only loss is symbolized as

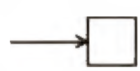


where the box represents the compartment and the arrow indicates a loss pathway. Other examples of simple conceptual models are

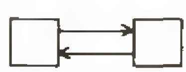
Single compartment with intake and loss



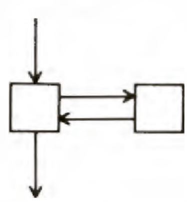
Sink compartment



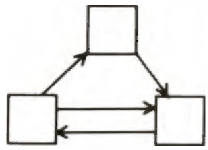
Closed two-compartment system with interchange



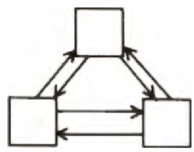
Open two-compartment system with interchange



Closed three-compartment system with partial interchange

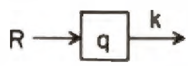


Closed three-compartment system with complete interchange



8. Mathematical Models

A mathematical model of a compartment system is a symbolic formulation which quantitatively describes behavior of the system. For example, the conceptual model



may be represented mathematically by the differential equation

$$\frac{dq}{dt} = R - kq$$

or by its solution

$$q = \frac{R}{k}(1 - e^{-kt}) + q(o)e^{-kt}$$

Mathematical models by necessity involve symbols of specific meaning and equations which relate the symbols. In the above example, t is the independent variable, q is the dependent variable, and R and k are constants whose values are characteristic of the system. Mathematical models may be deterministic, as in the example above, or stochastic. Stochastic models are probabilistic in that the constants are permitted to have probability distributions; thus the dependent variable takes on a probability distribution. The authors will have more to say about stochastic models later in the chapter, but in the meantime discussion will be restricted to deterministic models.

9. Some Common Symbols

Tracer kinetics involve a number of symbols so frequently that a brief review of them and their meaning is warranted:

t = Time. This is usually the independent variable.

Q_j = Amount of tracee in a compartment. Normally has units of grams. The subscript j refers to a specific compartment, compartment j.

q_j = Amount of tracer in compartment j. This normally has activity units (μCi), but may have mass units also.

a_j = q_j/Q_j. The ratio of tracer to tracee is called "specific activity". Subscript refers to compartment j.

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k = Rate constant, having units of t^{-1}. This term is often subscripted as k_{ij} to indicate the rate constant for transfer of tracer from compartment j to compartment i. Sometimes, the k term has a single subscript to represent a particular transport pathway as may be indicated in a conceptual model diagram. Use of a rate constant implies a first-order kinetic process, that is, the rate of transport is assumed proportional to the amount of tracer in the source compartment.

R = Rate of transport, having units of mass or activity per unit time. This term may also be subscripted in the same manner as rate constants. The value of R may be determined by various equations (eg, sections II.E and II.F earlier in this chapter). In the case of first-order tracer transport out of a compartment, R is given by the product kq. R may be time-dependent, and so-indicated by R(t).

τ = Mean lifetime or turnover time of a tracer quantity in a compartment. This is the reciprocal of the rate constant ($\tau = 1/k$) for a compartment exhibiting a single loss pathway. The relationship between τ and k is derived as follows:

For:

$$\boxed{q} \xrightarrow{k}$$

$$q(t) = q(o)\,e^{-kt}$$

$$\tau = \frac{\int_o^\infty q(t)dt}{q(o)} = \int_o^\infty e^{-kt}\,dt = \frac{1}{k}$$

$T_{1/2}$ = Half-time in the case of the tracer content in a compartment, or half-life in the case of radioactive decay. This is the time required for the amount of tracer material in a compartment to decrease by a factor of two. $T_{1/2}$ is related to k by

$$T_{1/2} = \frac{\ln 2}{k}$$

The derivation for the system

$$\boxed{q} \xrightarrow{k}$$

is

$$q(t) = q(o)\,e^{-kt}$$

$$q(t) = 2\,q(t)\,e^{-k\,T_{1/2}}$$

$$e^{kT_{1/2}} = 2$$

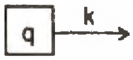
$$kT_{1/2} = \ln 2$$

$$T_{1/2} = \frac{\ln 2}{k}$$

B. Single-Compartment Systems with Constant Input Rates

In this section the authors will consider single compartments which exhibit first-order loss processes and which have input rates that are constant in time. The authors shall begin with the simplest case, alluded to several times previously in this chapter.

Model



Differential Equation

$$\frac{dq}{dt} = -kq$$

Solution

$$\frac{dq}{q} = -k\,dt$$

$$\ln q = -k\int dt$$

$$\ln q = -k\,t + C$$

Evaluating the constant of integration (C) for q = q(o) at t = 0,

$$C = \ln q(o)$$

$$\ln q = -kt + \ln q(o)$$

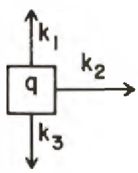
and

$$q = q(o)\,e^{-kt} \qquad (117)$$

In this case, an initial amount of tracer, q(o) is placed in the compartment and it is permitted to exit via a single pathway.

In many compartments, we find more than one exit pathway. For example, an animal as a compartment may lose an initial dose of tracer via urine, feces, and radioactive decay. The first-order model for this situation is

Model



Differential equation

$$\frac{dq}{dt} = -(k_1 + k_2 + k_3)q$$

Solution

Using the same method as for Equation 117,

$$q = q(o)\,e^{-(k_1 + k_2 + k_3)t} \tag{118}$$

In compartments with multiple first-order exit pathways, it is convenient to denote the model in general terms

$$q = q(o)\,e^{-k_{eff}t} \tag{119}$$

where

$$k_{eff} = \sum_{i=1}^{n} k_i$$

The term k_{eff} is called the "effective rate constant" and it in turn is related to the effective half-time (T_{eff}) by:

$$k_{eff} = \frac{\ln 2}{T_{eff}}$$

Next, let us turn our attention to single compartments which are receiving tracer inputs at constant rates. First, consider the sink compartment, i.e., a compartment with no exit pathway.

Model

$$R \longrightarrow \boxed{q}$$

Differential equation

$$\frac{dq}{dt} = R$$

Solution

$$dq = R\,dt$$

$$q = R\int dt$$

$$q = Rt + C$$

Evaluating C for $q = q(o)$ at $t = 0$,

$$q = Rt + q(o) \tag{120}$$

This model exhibits a linear accumulation of material in the compartment with time, and of course would apply only to very long-lived radionuclides or stable substances.

Much more common is the situation where material enters the compartment at a constant rate (R) and also has opportunity to exit by a first-order process.

Model

$$R \longrightarrow \boxed{q} \xrightarrow{k}$$

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Differential equation

$$\frac{dq}{dt} = R - kq$$

Solution

$$\frac{dq}{dt} + kq = R$$

Multiplying by the integration factor e^{kt}

$$\frac{dq}{dt} e^{kt} + kqe^{kt} = Re^{kt}$$

$$\frac{dq}{dt} e^{kt} + q \frac{de^{kt}}{dt} = Re^{kt}$$

$$\frac{d}{dt}(qe^{kt}) = Re^{kt}$$

$$qe^{kt} = R\int e^{kt}dt$$

$$qe^{kt} = \frac{R}{k} e^{kt} + C$$

Evaluating C for $q = q(o)$ at $t = 0$,

$$C = q(o) - \frac{R}{k}$$

and

$$qe^{kt} = \frac{R}{k} e^{kt} + q(o) - \frac{R}{k}$$

$$q = \frac{R}{k} + q(o)\, e^{-kt} - \frac{R}{k} e^{-kt}$$

$$q = \frac{R}{k}(1 - e^{-kt}) + q(o)\, e^{-kt} \qquad (121)$$

Should $q = 0$ at $t = 0$, then Equation 121 simplifies to

$$q = \frac{R}{k}(1 - e^{-kt}) \qquad (122)$$

It is important to examine this equation and its graphical form (Figure 22) in some detail because of its fundamental importance in radioecology. First, the equilibrium value of q is given by R/k. Thus, q is proportional to R and also to $T_{1/2}$ because of the inverse relation between k and $T_{1/2}$. The buildup portion of the equation, $1-e^{-kt}$, indicates the fraction of the equilibrium value attained at some value of t. As t becomes large, $(1-e^{-kt})$ approaches 1.0 asymtotically. It may be observed in Figure 22 that 0.5 of the equilibrium value is attained after one half-time. After five half-times, 0.97 of the equilibrium value is achieved and for practical purposes, equilibrium may be assumed. Equilibrium implies that the tracer is entering and leaving the compartment at the same rate,

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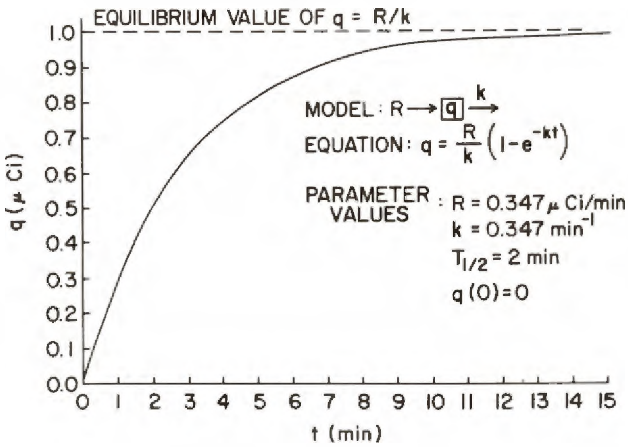


FIGURE 22. Graphical form of radionuclide accumulation in a single compartment receiving a constant input (R) and exhibiting first-order loss.

$$\text{Rate of entry} = \text{Rate of loss}$$

$$R = kq \tag{123}$$

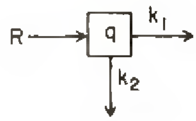
Therefore,

$$\frac{dq}{dt} = 0$$

It is clear from Figure 22 that dq/dt declines from a maximal value at t = 0 to near zero as q, and thus the rate of loss (kq) increases.

One may now proceed to other variations of the single compartment model with constant input rates. For example, in the system

Model

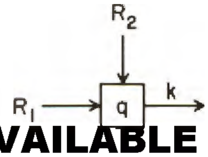


Solution

$$q = \frac{R}{k_1 + k_2}\left[1 - e^{-(k_1 + k_2)t}\right] + q(o)e^{-(k_1 + k_2)t} \tag{124}$$

As before, the rate constants k_1 and k_2, when summed, constitute an effective rate constant k_{eff}. In many situations, compartments may have multiple sources of income, and this is handled simply

Model



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Solution

$$q = \frac{R_1 + R_2}{k}(1 - e^{-kt}) + q(o)e^{-kt} \tag{125}$$

As with rate constants for exit from a single compartment, separate input rates to the same compartment may be summed, providing they are constant in time. Finally, for compartments having multiple inputs and multiple loss pathways, one may write a generalized solution

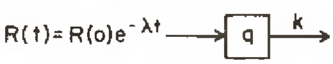
$$q = \frac{\sum_{j=1}^{m} R_j}{\sum_{i=1}^{n} k_i}\left[1 - e^{-\left(\sum_{i=1}^{n} k_i\right)t}\right] + q(o)e^{-\left(\sum_{i=1}^{n} k_i\right)t} \tag{126}$$

C. Single-Compartment Systems with Time-Variable Input Rates

We are now ready to consider single-compartment systems which are subject to time-variable input rates. In nature, variability and change seem to predominate over constancy. In radioecology, this also seems the rule. Systems of the following form will be discussed

where R(t) may exhibit exponential, linear, power, and cyclic time-dependencies. Let us first examine the simple exponential case

Model



Differential equation

$$\frac{dq}{dt} = R(o)e^{-\lambda t} - kq$$

Solution

$$\frac{dq}{dt} + kq = R(o)e^{-\lambda t}$$

Multiplying by the integration factor e^{kr}

$$\frac{dq}{dt}e^{kt} + kqe^{kt} = R(o)e^{(k-\lambda)t}$$

$$\frac{dq}{dt}e^{kt} + q\frac{de^{kt}}{dt} = R(o)e^{(k-\lambda)t}$$

$$\frac{d}{dt}(qe^{kt}) = R(o)e^{(k-\lambda)t}$$

$$qe^{kt} = R(o)\int e^{(k-\lambda)t}dt$$

$$qe^{kt} = \frac{R(o)}{k-\lambda} e^{(k-\lambda)t} + C$$

For $q = q(o)$ at $t = 0$,

$$C = q(o) - \frac{R(o)}{k-\lambda}$$

and

$$qe^{kt} = \frac{R(o)}{k-\lambda} e^{(k-\lambda)t} + q(o) - \frac{R(o)}{k-\lambda}$$

$$q = \frac{R(o)}{k-\lambda} e^{-\lambda t} + q(o)e^{-kt} - \frac{R(o)}{k-\lambda} e^{-kt}$$

$$q = \frac{R(o)}{k-\lambda} (e^{-\lambda t} - e^{-kt}) + q(o)e^{-kt} \qquad (127)$$

For $q(o) = 0$, this relation reduces to

$$q = \frac{R(o)}{k-\lambda} (e^{-\lambda t} - e^{-kt}) \qquad (128)$$

A typical plot of an equation of the above form is given in Figure 23 to illustrate its general shape. Note that the curve reaches a maximum and declines thereafter. The rate at which the maximum is reached is governed largely by the value of λ, while the rate of decline following the maximum is ultimately governed by k. Both λ and k affect the time at which q is maximal. This may be shown by taking the derivative of Equation 128

$$\frac{dq}{dt} = \frac{R(o)}{k-\lambda} (-\lambda e^{-\lambda t}) - \frac{R(o)}{k-\lambda} (-ke^{-kt})$$

Since $dq/dt = 0$ at the time (t_{max}) when q is maximal

$$\lambda e^{-\lambda t_{max}} = ke^{-kt_{max}}$$

Solving for t_{max}

$$e^{(k-\lambda)t_{max}} = \frac{k}{\lambda}$$

$$(k-\lambda)t_{max} = \ln (k/\lambda)$$

$$t_{max} = \frac{\ln (k/\lambda)}{k-\lambda} \qquad (129)$$

An interesting situation arises in the above model if $k = \lambda$. In this case, Equations 127 to 129 become undefined, and therefore, are not valid. However, the problem can be handled by rederiving the relation between q and t. Since $k = \lambda$, set $\lambda = k$ and rewrite the differential equation

$$\frac{dq}{dt} = R(o)e^{-kt} - kq$$

$$\frac{dq}{dt} + kq = R(o)e^{-kt}$$

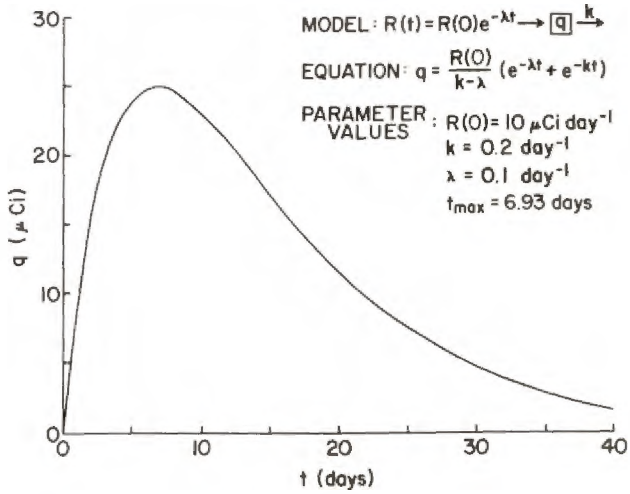


FIGURE 23. Plot of radionuclide content in a compartment receiving material at an exponentially decreasing rate.

multiplying through by e^{kt}

$$\frac{dq}{dt} e^{kt} + kqe^{kt} = R(o)$$

which leads to the solution

$$q = R(o)\, t\, e^{-kt} + q(o)\, e^{-kt} \tag{130}$$

It is also common to observe exponential intake functions with multiple components. For example, let us consider the case where $R(t) = R(o)\,(a\,e^{-\lambda_1 t} + b\,e^{-\lambda_2 t})$.

Model

$$R(t) = R(o)\left(a\,e^{-\lambda_1 t} + b\,e^{-\lambda_2 t}\right) \longrightarrow \boxed{q} \xrightarrow{k}$$

Differential equation

$$\frac{dq}{dt} = R(o)\,a\,e^{-\lambda_1 t} + R(o)\,b\,e^{-\lambda_2 t} - kq$$

Solution

The same approach used previously, that of rearranging the equation and multiplying through by the integrating factor e^{kt} is used to obtain

$$q = \frac{R(o)a}{k-\lambda_1}\left(e^{-\lambda_1 t} - e^{-kt}\right) + \frac{R(o)b}{k-\lambda_2}\left(e^{-\lambda_2 t} - e^{-kt}\right) + q(o)e^{-kt} \tag{131}$$

This approach may be used to obtain solutions for any number of exponential terms in the intake function.

The next problem is that of an exponential intake function which is building up rather than decreasing with time. For instance, let us look at the situation where R(t)

$= R(eq)\ (1-e^{-\lambda t})$. Here, $R(t)$ is building up to some maximum or equilibrium value, $R(eq)$.

Model

$$R(t) = R(eq)\left(1-e^{-\lambda t}\right) \longrightarrow \boxed{q} \xrightarrow{k}$$

Differential equation

$$\frac{dq}{dt} = R(eq)\ (1-e^{-\lambda t}) - kq$$

Solution

As before, one may use the integrating factor e^{kt} to obtain the solution

$$q = \frac{R(eq)}{k}\ (1-e^{-kt}) - \frac{R(eq)}{k-\lambda}\ (e^{-\lambda t} - e^{-kt}) + q(o)e^{-kt} \tag{132}$$

Although, not perhaps, as common as the exponential functions, the linear intake function deserves mention. This is of the form $R(t) = a\,t + R(o)$, where a is a constant having units of $\mu Ci/t^2$.

Model

$$R(t) = a\,t + R(o) \longrightarrow \boxed{q} \xrightarrow{k}$$

Differential equation

$$\frac{dq}{dt} = a\,t + R(o) - kq$$

Solution

As before, the integrating factor e^{kt} may be used to obtain

$$q = \frac{a}{k^2}\left(e^{-kt} + kt - 1\right) + \frac{R(o)}{k}\ (1-e^{-kt}) + q(o)e^{-kt} \tag{133}$$

In using the linear intake function, if $R(o)$ is some positive value and a is negative, Equation 133 is valid only over the time domain in which $R(t)$ is positive, i.e., it is required that the term $at \leqslant R(o)$. This is intuitive because a negative intake is clearly impossible. Note that if the intake function is constant, a becomes zero and the equation reduces to the same form as derived previously (Equation 121).

Intakes which vary as a power function of time are somewhat more difficult to handle, since exact solutions do not generally exist. This may be illustrated for the function $R(t) = R(1)t^p$, where p is positive.

Model

$$R(t) = R(1)t^p \longrightarrow \boxed{q} \xrightarrow{k}$$

Differential equation

$$\frac{dq}{dt} = R(1)\,t^p - kq$$

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Solution

$$q = R(1)e^{-kt}\int t^p e^{kt}\,dt$$

$$q = R(1)e^{-kt}\left[\frac{t^p e^{kt}}{k} - \frac{p}{k}\int t^{p-1} e^{kt}\,dt\right] \qquad (134)$$

For the case where p is negative but $\neq -1$

$$q = R(1)e^{-kt}\left[-\frac{e^{kt}}{(p-1)t^{p-1}} + \frac{k}{p-1}\int \frac{e^{kt}}{t^{p-1}}\,dt\right] \qquad (135)$$

Depending on the values of p, it may be more productive to handle power function intakes numerically by computer than to carry out many repetitive integrations.

Intakes which are cyclic may be handled mathematically, provided they may be described by a simple sine or cosine function. For example, if $R(t) = a \sin bt + \bar{R}$, where a determines the magnitude of the oscillations, b is 2π/cycle length, and $\bar{R}$ is the mean intake rate, there is a solution.

Model

$$R(t) = a \sin bt + \bar{R} \longrightarrow \boxed{q} \xrightarrow{k}$$

Differential equation

$$\frac{dq}{dt} = a \sin bt + \bar{R} - kq$$

Solution

By use of the integrating factor e^{kt}, one may obtain

$$qe^{kt} = a\int e^{kt} \sin bt\,dt + \bar{R}\int e^{kt}\,dt$$

which has the following solution for $q = q(o)$ at $t = 0$,

$$q = \frac{a}{k^2 + b^2}(k \sin bt - b \cos bt + be^{-kt})$$

$$+ \frac{\bar{R}}{k}(1 - e^{-kt}) + q(o)e^{-kt} \qquad (136)$$

A plot of such a function exhibits cyclic oscillations of q in response to the intake function parameters (Figure 24). The degree of responsiveness in q is dependent upon the magnitude of k in relation to the parameters a and b. If k is relatively large as in the example portrayed graphically, then q will oscillate measureably, displaying some lag with regard to R(t). In the example, the lag in peak values is about 4.5 hr. The mean value of q over n (integer) cycles is $\bar{R}/k$ as is intuitive. A cosine intake function may be handled in a fashion similar to the sine function, with a comparable solution.

D. Application of the Convolution Integral to Single Compartments

The convolution integral is frequently a useful tool in the analysis of compartments subjected to a variety of input functions and exhibiting several types of loss functions.

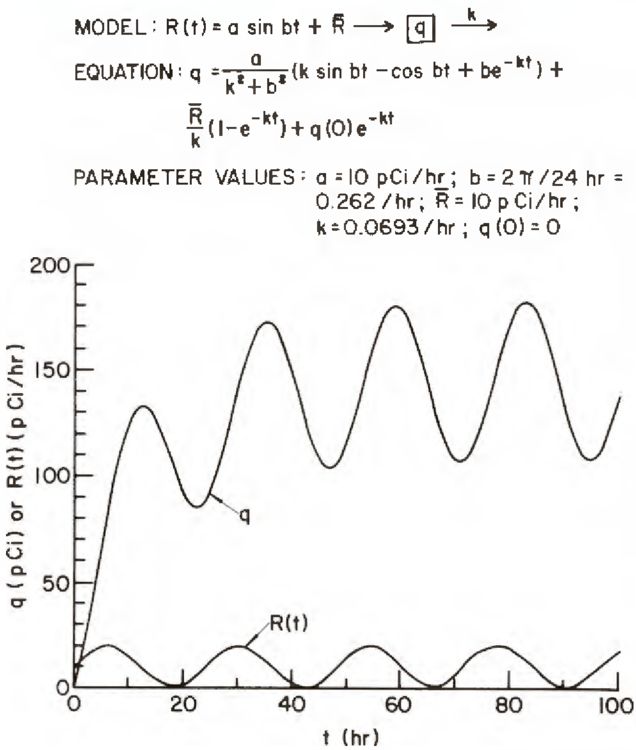

FIGURE 24. Plot of radionuclide content in a compartment that receives input according to a sine function. Period and magnitude of oscillations depend upon the equation parameters.

The convolution integral concept has been commonplace in the engineering fields for many years, but it has been used to only a limited extent in biology. Nevertheless, possible applications of the method in physiology and ecology for example, are numerous and undoubtedly growing.

The basic utility of the convolution integral is that it provides a general method of estimating the content of tracer in a compartment through time, q(t), provided that the intake R(t) and loss functions L(t) are known. The basic forms of the convolution integral as the authors shall use them are

$$q(t) = \int_0^t R(T)\, L(t - T)\, dT \tag{137}$$

and

$$q(t) = \int_0^t R(t - T)\, L(T)\, dT \tag{138}$$

Note the introduction of T, which is a time scale that is subsidiary to the basic time scale t.

Having stated the convolution integral, or as it is variously known by other names such as Duhamel's integral and the superposition integral, let us try to gain some insight as to its meaning and derivation.

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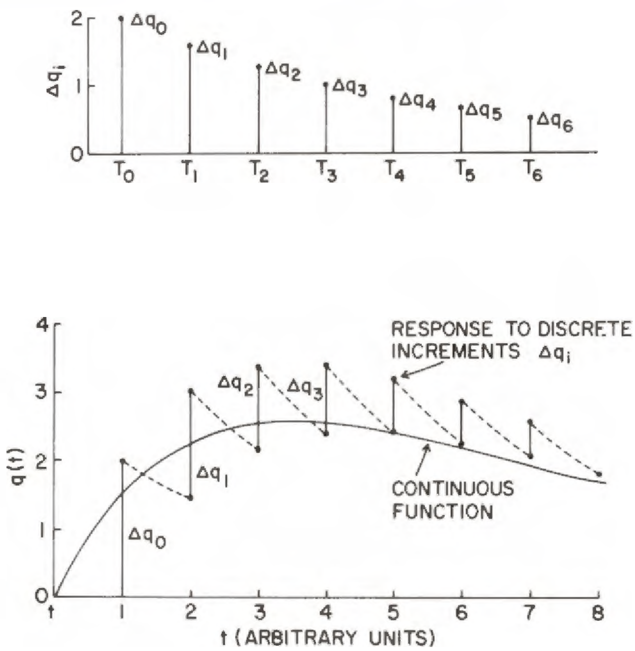

FIGURE 25. Response of a compartment q(t) to periodic increments Δq_i. The loss function of the compartment is $e^{-k(t-T)}$ where k is 0.347/unit (t-T). The continuous function of q(t) is derived from the convolution integral where the input function is continuous and given by $2e^{-0.231T}$.

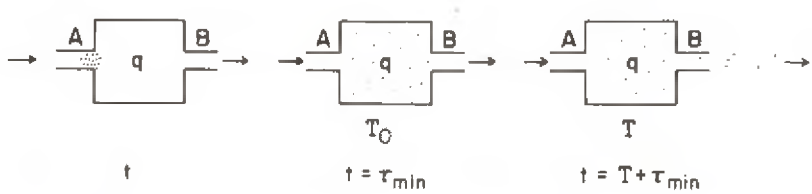

FIGURE 26. Conceptual diagram of a compartment with tracer (dots) entering at point A and exiting at point B. Also shown are the time scales t and T and their relationship. The minimum transit time through the compartment is τ_{min}.

Referring to Figure 25, suppose that at regular intervals of time an amount of tracer Δq_0, Δq_1, Δq_2, etc. is placed into the compartment. In most real compartments it takes a certain amount of time from tracer entry to the point at which a portion of the tracer can exit. In other words, a tracer introduced to a compartment at point A does not mix throughout the compartment instantaneously (Figure 26). Its exit, say at point B, may not occur until some bit of the tracer has had time to travel from point A to point B. This necessitates the use of a subsidiary time scale T. Thus, T_o is the point in time when the tracer dose may begin to exit the compartment. The retention or loss function is timed on the scale of (t-T) and it is symbolized as L(t-T). Remember, the loss function as used in this text is the fraction of the dose retained as a function of time (Equation 90). The interval of time between t_o and T_o is τ_{min}, the minimum transit time for any bit of tracer to travel from point A to point B.

Now then, going back to Figure 25, each bit of tracer that has been in the compartment for a length of time τ_{min}, is retained by the compartment according to L(t-T).

For example, Δq_0 is retained according to $L(t-T_0)$, Δq_1 according to $L(t-T_1)$, and so on. Thus, one may consider the following scheme

Time interval	q(t)
$T_0 < t < T_1$	$\Delta q_0\, L(t-T_0)$
$T_1 < t < T_2$	$\Delta q_0\, L(t-T_0) + \Delta q_1\, L(t-T_1)$
$T_2 < t < T_3$	$\Delta q_0\, L(t-T_0) + \Delta q_1\, L(t-T_1) + \Delta q_2\, L(t-T_2)$

and generalizing for $T_n < t < T_{n+1}$,

$$q(t) = \sum_{i=0}^{n} \Delta q_i \, L(t - T_i) \tag{139}$$

Let us next consider the Δq_i in the above example. The Δq_i are treated as discrete events or spikes. However, suppose that we treat the Δq_i as a continuous function of time, timed on the scale of T, so one now has $\Delta q(T)$. Furthermore, each increment in q is the product of the continuous rate of entry $R(T)$ and some increment of time (ΔT)

$$\Delta q(T) \cong R(T)\Delta T \tag{140}$$

Now, substituting the expression $R(T)\Delta T$ for Δq_i in Equation 139 one obtains

$$q(t) \cong \sum_{i=0}^{n} R(T)\, L(t - T_i)\Delta T \tag{141}$$

The limit of this expression as $\Delta T \rightarrow 0$ yields Equation 137. Equation 138 is derived from Equation 137 by a simple substitution.

One can say, therefore, that the convolution of the functions $R(t)$ and $L(t)$ is

$$R(t) \cdot L(t) = \int_0^t R(T)\, L(t - T)\, dT$$

and

$$R(t) \cdot L(t) = L(t) \cdot R(t) \tag{142}$$

As a means of demonstrating the validity of the convolution integral, let us apply it to the data in Figure 25. In this example, $R(T)$ is $R(o)e^{-\lambda T}$, where $R(o) = 2$ and λ is 0.231/unit T. Also, $L(t-T)$ is $e^{-k(t-T)}$, where k is 0.347/unit (t-T). Applying Equation 137,

$$q(t) = \int_0^t R(o)e^{-\lambda T}\, e^{-k(t-T)}\, dT$$

and solving

$$q(t) = R(o)e^{-kt} \int_0^t e^{(k-\lambda)T}\, dT$$

$$q(t) = \frac{R(o)e^{-kt}}{k - \lambda}\left[\left| e^{(k-\lambda)T} \right|_0^t\right]$$

$$q(t) = \frac{R(o)}{k - \lambda}\left(e^{-\lambda t} - e^{-kt}\right)$$

which is the same as Equation 128, derived earlier using the differential equation and integrating factor e^{kt}. Using the values given above for R(o), λ and k, one obtains the continuous function shown in Figure 25.

A quite useful and particularly simple application of the convolution integral is to the case where the intake function R(t) is constant through time. Here, one may apply Equation 138 and substitute R for R(t-T)

$$q(t) = \int_0^t R\,L(T)\,dT$$

which is equivalent to

$$q(t) = R\int_0^t L(t)\,dt \qquad (143)$$

This expression may be used to obtain solutions for q(t) for constant intake R and a variety of loss functions.

L(t)	q(t)
e^{-kt}	$\frac{R}{k}(1 - e^{-kt})$
$a_1e^{-\lambda_1 t} + a_2e^{-\lambda_2 t}$	$R\left[\frac{a_1}{\lambda_1}(1 - e^{-\lambda_1 t}) + \frac{a_2}{\lambda_2}(1 - e^{-\lambda_2 t})\right]$
$\sum_{i=1}^{n} a_i e^{-\lambda_i t}$	$R\sum_{i=1}^{n}\frac{a_i}{\lambda_i}(1 - e^{-\lambda_i t})$
t^p (p must be negative but $\neq -1$)	$R\int_1^t t^p dt = \frac{R}{p+1}(t^{p+1} - 1)$
t^{-1}	$R\int_1^t t^{-1}\,dt = R \ln t$

Many solutions to convolution problems can be obtained most conveniently by use of Laplace transforms,[91-95] which are reviewed in the next section. This method follows from Borel's Theorem which states that the convolution of two functions is equal to the inverse of the product of their transformations.

$$R(t) \cdot L(t) = \mathscr{L}^{-1}\left[\mathscr{L}\,R(t) \cdot \mathscr{L}\,L(t)\right]$$

Thus,

$$q(t) = \mathscr{L}^{-1}\left[\mathscr{L}\,R(t) \cdot \mathscr{L}\,L(t)\right] \qquad (144)$$

Let us consider an example where $R(t) = R(o)e^{-\lambda' t}$ and $L(t) = a_1e^{-\lambda_1 t} + a_2e^{-\lambda_2 t}$,

$$q(t) = \mathcal{L}^{-1}\left[\mathcal{L}(R(o)e^{-\lambda' t}) \cdot \mathcal{L}(a_1e^{-\lambda_1 t} + a_2e^{-\lambda_2 t})\right]$$

$$q(t) = \mathcal{L}^{-1}\left[\frac{R(o)}{s+\lambda'}\left(\frac{a_1}{s+\lambda_1} + \frac{a_2}{s+\lambda_2}\right)\right]$$

$$q(t) = \mathcal{L}^{-1}\left[\frac{a_1R(o)}{(s+\lambda')(s+\lambda_1)} + \frac{a_2R(o)}{(s+\lambda')(s+\lambda_2)}\right]$$

$$q(t) = \frac{a_1R(o)}{\lambda_1-\lambda'}(e^{-\lambda' t} - e^{-\lambda_1 t}) + \frac{a_2R(o)}{\lambda_2-\lambda'}(e^{-\lambda' t} - e^{-\lambda_2 t}) \tag{145}$$

The convolution integral as the authors have treated it in relation to radionuclide transport assumes that $q = 0$ at $t = 0$. If $q = q(o)$ initially, then one simply adds $q(o)L(t)$ to the solution obtained. Also, the authors have only considered certain continuous functions for intake and loss which have analytical solutions. It is worth noting that discrete time functions obtained by observations may be handled by the concepts of the convolution integral. Such functions may be solved numerically by use of computers.[96]

E. Two-Compartment First-Order Systems

In this section the authors shall examine closed and open two-compartment systems, in which the compartments exhibit first-order behavior. Solution of a two-compartment system implies that an expression for each compartment is obtained. If the two compartments are both in the system of concern, then they are assumed to be coupled. Thus the content of material in one is dependent upon the other and two equations must be solved simultaneously. Several, but not all possible conceptual models will be treated. Our main concern will be to demonstrate a feasible approach for the solution of the entire family of two-compartment first-order systems.

The recommended methodology consists of some five basic steps

1. Write the conceptual "box and arrow" model
2. Write the differential equations for each compartment
3. Take the Laplace transformation of each differential equation (this converts each to a linear algebraic equation)
4. Algebraically solve for the transforms of q_1 and q_2
5. Take the inverse Laplace transformation of each expression to yield $q_1(t)$ and $q_2(t)$

While it is not always necessary to use Laplace transforms to solve two-compartment systems, this is generally the most efficient way to obtain the desired solutions. It is usually possible to solve the differential equations by integration as has largely been done to this point, but as the models become more complex, this method becomes a bit cumbersome.

Before getting into some examples of two-compartment models, a brief review of Laplace transforms may be helpful. This transform is defined as

$$\mathcal{L}[f(t)] = F(s) = \int_0^\infty e^{-st} f(t)\, dt \tag{146}$$

where $\mathscr{L}$ [f(t)] is the notation meaning the Laplace transformation of some function f(t) and F(s) is the transform of f(t), employing a new independent variable s. The inverse Laplace transform is represented as

$$\mathscr{L}^{-1}\,[F(s)] = f(t) \tag{147}$$

The basic use of the Laplace transform is to find F(s) for some f(t), operate on the transform, and then obtain the desired solution by performing an inverse transformation. In many respects, this procedure is analogous to multiplying two numbers by summing their logarithms, then finding the product by taking the antilogarithm of the sum. A major utility of Laplace transforms in tracer kinetics is the conversion of linear differential equations to linear algebraic equations, which are more easily dealt with. In practice, there is usually no need to perform the integration of Equation 146 because tables of the more common transforms are available. A few of the transforms likely to be needed are given in Table 19.

Let us now deal with some two-compartment models and their solution. First, consider a closed system, with one compartment acting as a source, the other as a sink.

Model

$$\boxed{q_1} \xrightarrow{k} \boxed{q_2}$$

Differential equations

$$\frac{dq_1}{dt} = -kq_1$$

$$\frac{dq_2}{dt} = kq_1$$

Transformations

Let $F_1 = \mathscr{L}\ q_1 = F_1(s)$; $F_2 = \mathscr{L}\ q_2 = F_2(s)$

$$sF_1 - q_1(o) = -k\,F_1$$

$$sF_2 - q_2(o) = k\,F_1$$

Solution for q_1

$$sF_1 - q_1(o) = -k\,F_1$$

$$sF_1 + k\,F_1 = q_1(o)$$

$$F_1\,(s+k) = q_1(o)$$

$$F_1 = \frac{q_1(o)}{s+k}$$

Using Table 19

$$q_1(t) = \mathscr{L}^{-1}\,F_1 = q_1(o)e^{-kt} \tag{148}$$

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Table 19
SOME COMMON FUNCTIONS AND THEIR LAPLACE TRANSFORMATIONS

Function [f(t)]	Transform [F(s)]
$a\,f(t)$	$a\,F(s)$
$a\,f_1(t) + b\,f_2(t)$	$a\,F_1(s) + b\,F_2(s)$
$f\left(\frac{t}{a}\right)$	$a\,F(a\,s)$
t	$\frac{1}{s^2}$
a	$\frac{a}{s}$
$\frac{d\,f(t)}{dt}$	$s\,F(s) - f(o)$
$\sin a\,t$	$\frac{a}{s^2 + a^2}$
$e^{-\gamma t}$	$\frac{1}{s + \gamma}$
$t\,e^{-\gamma t}$	$\frac{1}{(s + \gamma)^2}$
$\frac{1}{\gamma}\,(1 - e^{-\gamma t})$	$\frac{1}{s(s+\gamma)}$
$\frac{e^{-\gamma t} - e^{-\delta t}}{\delta - \gamma}$	$\frac{1}{(s+\gamma)\,(s+\delta)}$
$\frac{(a-\delta)\,e^{-\delta t} - (a-\gamma)\,e^{-\gamma t}}{\gamma - \delta}$	$\frac{s+a}{(s+\gamma)\,(s+\delta)}$
$\frac{1}{\gamma\delta} + \frac{\gamma e^{-\delta t} - \delta e^{-\gamma t}}{\gamma\delta(\delta - \gamma)}$	$\frac{1}{s(s+\gamma)\,(s+\delta)}$
$\frac{a}{\gamma\delta} + \frac{(a-\gamma)e^{-\gamma t}}{\gamma(\gamma-\delta)} + \frac{(a-\delta)e^{-\delta t}}{\delta(\delta-\gamma)}$	$\frac{s+a}{s(s+\gamma)\,(s+\delta)}$
$\frac{a}{\gamma\delta} + \frac{(\gamma^2 - b\gamma + a)\,e^{-\gamma t}}{\gamma(\gamma-\delta)} + \frac{(\delta^2 - b\delta + a)\,e^{-\delta t}}{\delta(\delta-\gamma)}$	$\frac{s^2 + b\,s + a}{s(s+\gamma)\,(s+\delta)}$

Note: Symbols a, b, γ, and δ represent constants.

Solution for q_2

$$sF_2 - q_2(o) = k\,F_1$$

since

$$F_1 = \frac{q_1(o)}{s+k}$$

$$sF_2 - q_2(o) = \frac{k\,q_1(o)}{s+k}$$

$$F_2 = \frac{k\,q_1(o)}{s(s+k)} + \frac{q_2(o)}{s}$$

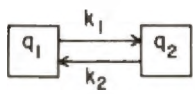
Using Table 19

$$q_2(t) = \mathscr{L}^{-1}\,F_2 = \frac{k\,q_1(o)}{k}\left(1 - e^{-kt}\right) + q_2(o)$$

$$q_2(t) = q_1(o)\left(1 - e^{-kt}\right) + q_2(o) \qquad (149)$$

Equations 148 and 149 thus represent the solution to the system.
Next, consider a closed two-compartment system with interchange.

Model



Differential equations

$$\frac{dq_1}{dt} = k_2\,q_2 - k_1\,q_1$$

$$\frac{dq_2}{dt} = k_1\,q_1 - k_2\,q_2$$

Transformations

$$sF_1 - q_1(o) = k_2\,F_2 - k_1\,F_1$$

$$sF_2 - q_2(o) = k_1\,F_1 - k_2\,F_2$$

Solution for q_1
Eliminating F_2 from the transformed differential equations,

$$sF_1 - q_1(o) = k_2\left[\frac{k_1 F_1}{s+k_2} + \frac{q_2(o)}{s+k_2}\right] - k_1\,F_1$$

solving for F_1 and rearranging to forms found in Table 19,

$$F_1 = \frac{k_2\left[q_1(o) + q_2(o)\right]}{s(s+k_1+k_2)} + \frac{q_1(o)}{s+k_1+k_2}$$

letting $\gamma = k_1 + k_2$,

$$F_1 = \frac{k_2[q_1(o) + q_2(o)]}{s(s+\gamma)} + \frac{q_1(o)}{s+\gamma}$$

$$q_1(t) = \mathscr{L}^{-1} F_1 = \frac{k_2[q_1(o) + q_2(o)]}{\gamma}(1 - e^{-\gamma t})$$

$$+ q_1(o)e^{-\gamma t}$$

and finally, replacing γ with $k_1 + k_2$,

$$q_1(t) = \frac{k_2[q_1(o)+q_2(o)]}{k_1+k_2}\left[1-e^{-(k_1+k_2)t}\right] + q_1(o)e^{-(k_1+k_2)t} \qquad (150)$$

Solution for q_2

Eliminating F_1 from the transformed differential equations,

$$sF_2 - q_2(o) = k_1\left[\frac{k_2F_2}{s+k_1} + \frac{q_1(o)}{s+k_1}\right] - k_2F_2$$

solving for F_2, rearranging to forms found in Table 19, and letting $\gamma = k_1 + k_2$,

$$F_2 = \frac{k_1[q_1(o) + q_2(o)]}{s(s+\gamma)} + \frac{q_2(o)}{s+\gamma}$$

Taking the inverse and replacing γ with $k_1 + k_2$,

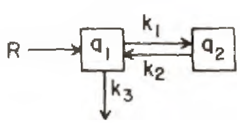
$$q_2(t) = \frac{k_1[q_1(o) + q_2(o)]}{k_1 + k_2}[1 - e^{-(k_1 + k_2)t}]$$

$$+ q_2(o)e^{-(k_1 + k_2)t} \qquad (151)$$

Curves for a two-compartment closed system with interchange are shown in Figure 15.

Next, let us examine the more common (and more complex) case of an open two-compartment system with interchange. The case where compartment 1 is receiving tracer at some rate R from outside the system and also releasing tracer to the outside, but at the same time is exchanging with another compartment, is rather common.[73] The solution to this system is obtained as follows:

Model



Differential equations

$$\frac{dq_1}{dt} = R + k_2q_2 - (k_1 + k_3)q_1$$

$$\frac{dq_2}{dt} = k_1q_1 - k_2q_2$$

Transformations

$$sF_1 - q_1(o) = \frac{R}{s} + k_2 F_2 - (k_1 + k_3) F_1$$

$$sF_2 - q_2(o) = k_1 F_1 - k_2 F_2$$

Solution for q_1

Eliminating F_2 from the transformed differential equations,

$$sF_1 - q_1(o) = \frac{R}{s} + k_2 \left[\frac{k_1 F_1}{s + k_2} + \frac{q_2(o)}{s + k_2}\right] - (k_1 + k_3) F_1$$

solving for F_1 and rearranging to forms in Table 19,

$$F_1 = \frac{R + k_2 q_2(o) + q_1(o)(s + k_2) + \dfrac{k_2 R}{s}}{s^2 + (k_1 + k_2 + k_3) s + k_2 k_3}$$

by use of the quadratic equation, the denominator has the roots γ and δ, where

$$\gamma = \frac{(k_1 + k_2 + k_3) - [(k_1 + k_2 + k_3)^2 - 4 k_2 k_3]^{1/2}}{2}$$

and

$$\delta = \frac{(k_1 + k_2 + k_3) + [(k_1 + k_2 + k_3)^2 - 4 k_2 k_3]^{1/2}}{2}$$

Note that the first term of the numerator of each root becomes positive since the rate constants are negative. The denominator of the expression for F_1 above is thus $(s + \gamma)(s + \delta)$ and,

$$F_1 = \frac{R + k_2 q_2(o)}{(s + \gamma)(s + \delta)} + \frac{q_1(o)(s + k_2)}{(s + \gamma)(s + \delta)} + \frac{k_2 R}{s(s + \gamma)(s + \delta)}$$

Taking the inverse,

$$q_1(t) = \frac{R + k_2 q_2(o)}{\delta - \gamma}(e^{-\gamma t} - e^{-\delta t})$$

$$+ \frac{q_1(o)}{\gamma - \delta}\left[(k_2 - \delta)e^{-\delta t} - (k_2 - \gamma)e^{-\gamma t}\right]$$

$$+ k_2 R \left[\frac{1}{\gamma\delta} + \frac{\gamma e^{-\delta t} - \delta e^{-\gamma t}}{\gamma(\delta - \gamma)}\right]$$

This simplifies (slightly) by gathering exponential terms to

$$q_1(t) = \frac{k_2 R}{\gamma\delta} + \left[\frac{R(1 - k_2/\gamma) + q_1(o)(k_2 - \gamma) + k_2 q_2(o)}{\delta - \gamma}\right] e^{-\gamma t}$$

$$+ \left[\frac{R(1 - k_2/\delta) + q_1(o)(k_2 - \delta) + k_2 q_2(o)}{\gamma - \delta}\right] e^{-\delta t}$$

Solution for q_2

Eliminating F_1 from the transformed differential equations,

$$s\,F_2 - q_2(o) = k_1 \left[\frac{R/s + k_2\,F_2 + q_1(o)}{s + k_1 + k_3}\right] - k_2\,F_2$$

solving for F_2 and rearranging to forms in Table 19,

$$F_2 = \frac{k_1\,q_1(o) + q_2(o)\,(s + k_1 + k_3) + \dfrac{k_1\,R}{s}}{s^2 + (k_1 + k_2 + k_3)\,s + k_2\,k_3}$$

The denominator has the same roots γ and δ as determined by the quadratic equation in the solution for q_1. Thus,

$$F_2 = \frac{k_1 q_1(o)}{(s+\gamma)\,(s+\delta)} + \frac{q_2(o)\,(s+k_1+k_3)}{(s+\gamma)\,(s+\delta)} + \frac{k_1\,R}{s(s+\gamma)\,(s+\delta)}$$

Taking the inverse,

$$q_2(t) = \frac{k_1 q_1(o)}{\delta - \gamma}\,(e^{-\gamma t} - e^{-\delta t})$$

$$+ \frac{q_2(o)}{\gamma - \delta}\,[(k_1 + k_3 - \delta)\,e^{-\delta t} - (k_1 + k_3 - \gamma)\,e^{-\gamma t}]$$

$$+ k_1\,R\left[\frac{1}{\gamma\delta} + \frac{\gamma e^{-\delta t} - \delta e^{-\gamma t}}{\gamma\delta\,(\delta - \gamma)}\right]$$

A slightly simpler form is obtained by gathering the exponential terms to

$$q_2(t) = \frac{k_1\,R}{\gamma\delta} + \left[\frac{k_1 q_1(o) + q_2(o)\,(k_1 + k_3 - \gamma) - k_1\,R/\gamma}{\delta - \gamma}\right] e^{-\gamma t}$$

$$+ \left[\frac{k_1 R/\delta - q_2(o)\,(k_1 + k_3 - \delta) - k_1 q_1(o)}{\delta - \gamma}\right] e^{-\delta t} \qquad (153)$$

The foregoing solutions are quite complex; however, they are general in that any initial conditions, $q_1(o)$ and $q_2(o)$ may be imposed. If $q_1(o)$ and $q_2(o)$ are set equal to zero, the equations simplify considerably. If one wished to predict the retention by the system of an acute dose placed into q_1, one simply sets $q_1(o)$ = dose and $R = q_2(o) = 0$, and add the resulting expressions for $q_1(t)$ and $q_2(t)$.

The two-compartment system

$$R \longrightarrow \boxed{q_1} \xrightarrow{k_1} \boxed{q_2} \xrightarrow{k_2}$$

could be solved in the same manner as the previous example. However, the equations for this system have already been developed for the individual compartments. Equation 121 is the solution for q_1, while Equations 128 and 132 may be used for q_2. Thus, the solutions for this model become

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$$q_1(t) = \frac{R}{k_1}(1 - e^{-k_1 t}) + q_1(o)e^{-k_1 t}$$

and

$$q_2(t) = \frac{q_1(o)k_1}{k_2 - k_1}(e^{-k_1 t} - e^{-k_2 t}) + \frac{R}{k_2}(1 - e^{-k_2 t})$$

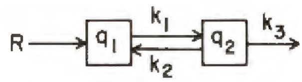
$$- \frac{R}{k_2 - k_1}(e^{-k_1 t} - e^{-k_2 t}) + q_2(o)e^{-k_2 t} \qquad (154)$$

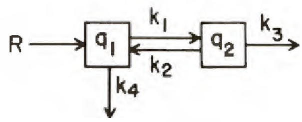
which simplifies to

$$q_2(t) = \frac{R}{k_2}(1 - e^{-k_2 t}) + \frac{q_1(o)k_1 - R}{k_2 - k_1}(e^{-k_1 t} - e^{-k_2 t})$$

$$+ q_2(o)e^{-k_2 t} \qquad (155)$$

Other examples of open two-compartment models may be encountered, such as





The solution to these may be obtained by the methods outlined in this section and the authors happily leave them as a challenge to the reader.

F. First-Order Systems with Three or More Compartments

As we obtain analytic solutions for systems of increasing complexity, we quickly find that the solutions become so cumbersome that it hardly seems worth the effort. Three-compartment systems can generally be solved with ordinary mathematical techniques, but at this point the bookkeeping becomes laborious and errors are easily made. Nevertheless, we shall go through a couple of examples for the purpose of illustrating some mathematical techniques. Even four-compartment systems may be handled with pencil and paper if the number of pathways is not too great. Systems of four or more compartments are normally best handled numerically by use of digital computers. Computer implementation of numerical procedures are beyond the scope of this text, but they will be discussed later in general terms.

Systems of three or more compartments are basically solved in the same manner as two-compartment systems. However, the step involving the simultaneous solution of the transformed differential equations becomes a larger task, and techniques of matrix algebra come into play. Also, since the equations are more complex than is the case for two-compartment systems, it may be difficult or impossible in certain cases to manipulate them into forms amenable to inverse Laplace transformation.

Having prepared but hopefully not discouraged the reader for what is to follow, let us plunge into the solution of a three-compartment system. Let us arbitrarily choose a closed system with complete interchange.

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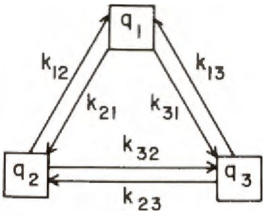
Model



Differential equations

$$\frac{dq_1}{dt} = k_{12} q_2 + k_{13} q_3 - (k_{21} + k_{31}) q_1$$

$$\frac{dq_2}{dt} = k_{21} q_1 + k_{23} q_3 - (k_{12} + k_{32}) q_2$$

$$\frac{dq_3}{dt} = k_{31} q_1 + k_{32} q_2 - (k_{23} + k_{13}) q_3$$

Laplace transformations

Letting $\mathscr{L}\ q_i = F_i$

$$sF_1 - q_1(o) = k_{12} F_2 + k_{13} F_3 - (k_{21} + k_{31}) F_1$$

$$sF_2 - q_2(o) = k_{21} F_1 + k_{23} F_3 - (k_{12} + k_{32}) F_2$$

$$sF_3 - q_3(o) = k_{31} F_1 + k_{32} F_2 - (k_{23} + k_{13}) F_3$$

Initial conditions and simplifying substitutions

Let $q_1 = q_1(o)$; $q_2 = 0$; and $q_3 = 0$ at $t = 0$

Let $k_1 = k_{21} + k_{31}$; $k_2 = k_{12} + k_{32}$; $k_3 = k_{23} + k_{13}$

Therefore, one can have the system of equations

$$sF_1 - q_1(o) = k_{12} F_2 + k_{13} F_3 - k_1 F_1$$

$$sF_2 - 0 = k_{21} F_1 + k_{23} F_3 - k_2 F_2$$

$$sF_3 - 0 = k_{31} F_1 + k_{32} F_2 - k_3 F_3$$

This system is ordered to facilitate its solution by matrix algebra as follows

$$(s + k_1) F_1 - k_{12} F_2 - k_{13} F_3 = q_1(o)$$

$$-k_{21} F_1 + (s + k_2) F_2 - k_{23} F_3 = 0$$

$$-k_{31} F_1 - k_{32} F_2 + (s + k_3) F_3 = 0$$

Matrix operations

At this point the authors are ready to solve for F_1, F_2, and F_3 as functions of the k_{ij},

k_{ij}, s, and $q_i(o)$. This may be accomplished by Cramer's Rule which states that for a system of equations such as

$$a_{11} X + a_{12} Y + a_{13} Z = b_1$$

$$a_{21} X + a_{22} Y + a_{23} Z = b_2$$

$$a_{31} X + a_{32} Y + a_{33} Z = b_3$$

the X, Y, and Z may be found by

$$X = \frac{|D_X|}{|D|} \; ; \; Y = \frac{|D_Y|}{|D|} \; ; \; Z = \frac{|D_Z|}{|D|}$$

where |D| is the determinant of the coefficient matrix,

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

$$|D| = a_{11} a_{22} a_{33} + a_{12} a_{23} a_{31} + a_{13} a_{21} a_{32} - a_{13} a_{22} a_{31} - a_{23} a_{32} a_{11} - a_{33} a_{12} a_{21}$$

$|D_x|$ is the determinant of the matrix,

$$\begin{bmatrix} b_1 & a_{12} & a_{13} \\ b_2 & a_{22} & a_{23} \\ b_3 & a_{32} & a_{33} \end{bmatrix}$$

$|D_y|$ is the determinant of the matrix,

$$\begin{bmatrix} a_{11} & b_1 & a_{13} \\ a_{21} & b_2 & a_{23} \\ a_{31} & b_3 & a_{33} \end{bmatrix}$$

and $|D_z|$ is the determinant of the matrix,

$$\begin{bmatrix} a_{11} & a_{12} & b_1 \\ a_{21} & a_{22} & b_2 \\ a_{31} & a_{32} & b_3 \end{bmatrix}$$

Applying the foregoing relationships to the problem at hand, one has for the coefficient matrix

$$\begin{bmatrix} s+k_1 & -k_{12} & -k_{13} \\ -k_{21} & s+k_2 & -k_{23} \\ -k_{31} & -k_{32} & s+k_3 \end{bmatrix}$$

Solving for the determinant of the coefficient matrix,

$$|D| = (s+k_1)(s+k_2)(s+k_3) - k_{12}k_{23}k_{31} - k_{13}k_{21}k_{32}$$
$$-k_{13}k_{31}(s+k_2) - k_{12}k_{21}(s+k_3) - k_{23}k_{32}(s+k_1)$$

Which simplifies to the quadratic form

$$|D| = s\left[s^2 + (k_1+k_2+k_3)s + (k_1k_2 + k_2k_3 + k_1k_3 - k_{13}k_{31} - k_{12}k_{21} - k_{23}k_{32})\right]$$

Similarly, it may be shown that

$$|D_X| = q_1(o)\left[s^2 + (k_2+k_3)s + k_2k_3 - k_{23}k_{32}\right]$$

$$|D_Y| = q_1(o)k_{21}\left[s + \left(k_{23} + k_{13} + \frac{k_{23}k_{31}}{k_{21}}\right)\right]$$

$$|D_Z| = q_1(o)k_{31}\left[s + \left(k_{12} + k_{32} + \frac{k_{21}k_{32}}{k_{31}}\right)\right]$$

At this point, it is again helpful to introduce some substitutions which simplify the bookkeeping.

Let $b = k_1 + k_2 + k_3$

$c = k_1k_2 + k_2k_3 + k_1k_3 - k_{13}k_{31} - k_{12}k_{21} - k_{23}k_{32}$

$d = k_2 + k_3$

$f = k_2k_3 - k_{23}k_{32}$

$$g = k_{23} + k_{13} + \frac{k_{23}k_{31}}{k_{21}}$$

$$h = k_{12} + k_{32} + \frac{k_{21}k_{32}}{k_{31}}$$

Solution for $q_1(t)$

From Cramer's Rule,

$$F_1 = \frac{|D_X|}{|D|} = \frac{q_1(o)(s^2 + ds + f)}{s(s^2 + bs + c)}$$

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Finding the roots of $s^2 + bs + c$,

$$F_1 = \frac{q_1(o)\,(s^2 + ds + f)}{s\,(s+\gamma)\,(s+\delta)}$$

where

$$\gamma = \frac{b - (b^2 - 4c)^{1/2}}{2}$$

and

$$\delta = \frac{b + (b^2 - 4c)^{1/2}}{2}$$

Taking the inverse of F_1 (Table 19),

$$q_1(t) = q_1(o)\left[\frac{f}{\gamma\delta} + \frac{(\gamma^2 - d\gamma + f)e^{-\gamma t}}{\gamma(\gamma-\delta)} + \frac{(\delta^2 - d\delta + f)e^{-\delta t}}{\delta(\delta-\gamma)}\right] \qquad (156)$$

Solution for $q_2(t)$

$$F_2 = \frac{|D_Y|}{|D|} = \frac{q_1(o)k_{21}\,(s+g)}{s(s+\gamma)\,(s+\delta)}$$

Taking the inverse,

$$q_2(t) = q_1(o)k_{21}\left[\frac{g}{\gamma\delta} + \frac{(g-\gamma)e^{-\gamma t}}{\gamma(\gamma-\delta)} + \frac{(g-\delta)e^{-\delta t}}{\delta(\delta-\gamma)}\right] \qquad (157)$$

Solution for $q_3(t)$

$$F_3 = \frac{|D_Z|}{|D|} = \frac{q_1(o)k_{31}\,(s+h)}{s(s+\gamma)\,(s+\delta)}$$

Taking the inverse,

$$q_3(t) = q_1(o)k_{31}\left[\frac{h}{\gamma\delta} + \frac{(h-\gamma)e^{-\gamma t}}{\gamma(\gamma-\delta)} + \frac{(h-\delta)e^{-\delta t}}{\delta(\delta-\gamma)}\right] \qquad (158)$$

Despite the complexity of these solutions, they are explicit and if the initial values of q_1 and the individual rate constants are known, the time courses of q_1, q_2, and q_3 can be plotted. An example with arbitrary values is shown in Figure 27.

Another commonly encountered example of a multicompartment system amenable to explicit solution is a series with one-way flows

$$\boxed{q_1} \xrightarrow{k_1} \boxed{q_2} \xrightarrow{k_2} \boxed{q_3} \xrightarrow{k_3} \boxed{q_4} \xrightarrow{k_4}$$

The radioactive decay series of natural uranium and thorium may be visualized according to this model, as can certain other compartment systems. Solutions to the decay

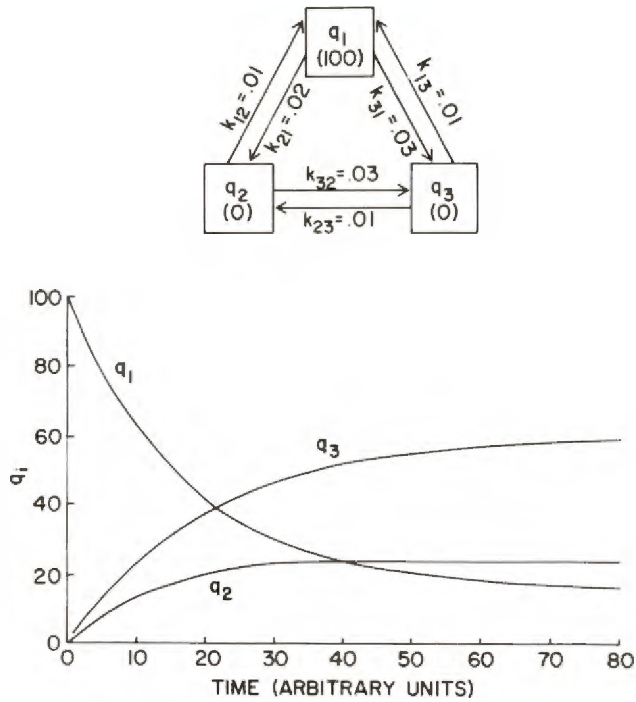

FIGURE 27. Graphical solution to the illustrated three-compartment model. Initial conditions are shown in parentheses and rate constant values are indicated in the conceptual model diagram. Solutions are given by Equations 156 to 158.

series are frequently known as the "Batemann equations". These equations may be derived rather conveniently by the use of Laplace transforms. Let us next develop these equations to illustrate the method as well as the form of the solutions. Referring to the series model above,

Differential equations

$$\frac{dq_1}{dt} = -k_1 q_1$$

$$\frac{dq_2}{dt} = k_1 q_1 - k_2 q_2$$

$$\frac{dq_3}{dt} = k_2 q_2 - k_3 q_3$$

$$\frac{dq_4}{dt} = k_3 q_3 - k_4 q_4$$

Laplace transformations and initial conditions

Letting $\mathscr{L}\ q_i = F_i$, $q_1(o) = q_1(o)$; and $q_2(o) = q_3(o) = q_4(o) = 0$

$$sF_1 - q_1(o) = -k_1 F_1$$

$$sF_2 - 0 = k_1 F_1 - k_2 F_2$$

$$sF_3 - 0 = k_2 F_2 - k_3 F_3$$

Solution for $q_1(t)$

Rearranging the transformed differential equation,

$$F_1 = \frac{q_1(o)}{s+k_1}$$

Taking the inverse,

$$q_1(t) = q_1(o)e^{-k_1 t} \tag{159}$$

Solution for $q_2(t)$

$$s F_2 = k_1F_1 - k_2F_2$$

since

$$F_1 = \frac{q_1(o)}{s+k_1}$$

$$s F_2 = \frac{k_1 q_1(o)}{s+k_1} - k_2 F_2$$

Solving for F_2,

$$F_2 = \frac{k_1 q_1(o)}{(s+k_1)(s+k_2)}$$

Taking the inverse,

$$q_2(t) = \frac{k_1 q_1(o)}{k_1 - k_2} (e^{-k_2 t} - e^{-k_1 t}) \tag{160}$$

Solution for $q_3(t)$

$$s F_3 = k_2F_2 - k_3F_3$$

since

$$F_2 = \frac{k_1 q_1(o)}{(s+k_1)(s_1+k_2)}$$

$$F_3 = \frac{k_1 k_2 q_1(o)}{(s+k_1)(s+k_2)(s+k_3)}$$

This form may now be changed to one amenable to inverse Laplace transformation through the use of partial fractions. Thus,

$$F_3 = \frac{W}{s+k_1} + \frac{X}{s+k_2} + \frac{Y}{s+k_3}$$

where

$$W = \frac{k_1 k_2 q_1(o)}{(k_2 - k_1)(k_3 - k_1)}$$

$$X = \frac{k_1 k_2 q_1(o)}{(k_1 - k_2)(k_3 - k_2)}$$

$$Y = \frac{k_1 k_2 q_1(o)}{(k_1 - k_3)(k_2 - k_3)}$$

Taking the inverse of F_3,

$$q_3(t) = W e^{-k_1 t} + X e^{-k_2 t} + Y e^{-k_3 t} \tag{161}$$

Solution for $q_4(t)$

$$s F_4 = k_3 F_3 - k_4 F_4$$

since

$$F_3 = \frac{k_1 k_2 q_1(o)}{(s+k_1)(s+k_2)(s+k_3)}$$

$$F_4 = \frac{k_1 k_2 k_3 q_1(o)}{(s+k_1)(s+k_2)(s+k_3)(s+k_4)}$$

Using partial fractions,

$$F_4 = \frac{A}{s+k_1} + \frac{B}{s+k_2} + \frac{C}{s+k_3} + \frac{D}{s+k_4}$$

where

$$A = \frac{k_1 k_2 k_3 q_1(o)}{(k_2 - k_1)(k_3 - k_1)(k_4 - k_1)}$$

$$B = \frac{k_1 k_2 k_3 q_1(o)}{(k_1 - k_2)(k_3 - k_2)(k_4 - k_2)}$$

$$C = \frac{k_1 k_2 k_3 q_1(o)}{(k_1 - k_3)(k_2 - k_3)(k_4 - k_3)}$$

$$D = \frac{k_1 k_2 k_3 q_1(o)}{(k_1 - k_4)(k_2 - k_4)(k_3 - k_4)}$$

Taking the inverse of F_4,

$$q_4(t) = A e^{-k_1 t} + B e^{-k_2 t} + C e^{-k_3 t} + D e^{-k_4 t} \tag{162}$$

A general pattern is evident from the foregoing solutions. This may be expressed as

$$q_n = q_1(o) \left[\prod_{i=1}^{n-1} k_i \right] \sum_{i=1}^{n} \left[\frac{e^{-k_i t}}{\prod_{j=1}^{n} (k_j - k_i)} \right] \tag{163}$$

where $j \neq i$, $q_1(o) = q_1(o)$; $q_2(o), q_3(o), \ldots q_n(o) = 0$, n = number in series ($n \neq 1$), Π signifies product of, and Σ signifies summation of. Should the initial conditions specify some finite quantities in compartments other than the first one in the series, the solutions could be determined by the same general method, but they would be more complex.

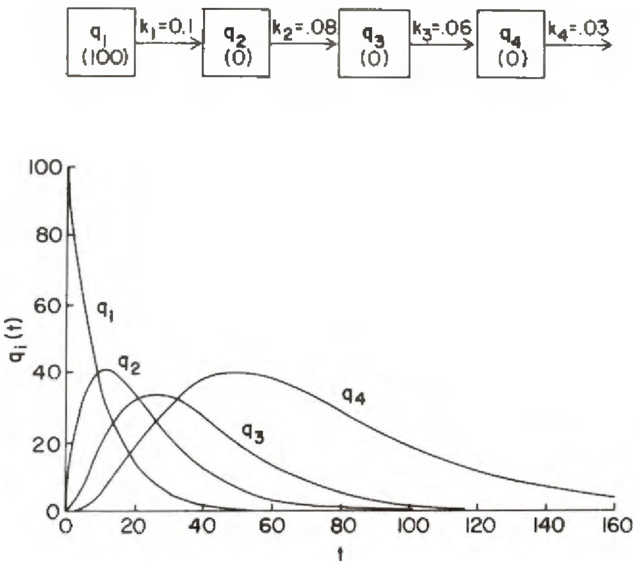

FIGURE 28. Graphical solution to the illustrated four-compartment model. Initial conditions are shown in parentheses and rate constants are indicated in the conceptual model diagram. Solutions are given by Equations 159 to 162.

For illustrative purposes, a graphical solution to a four compartment series is given in Figure 28. In this example, all the material is in the first compartment at t = 0 and the rate constants have arbitrary values.

Confusion can arise in the application of Equations 160 to 163 to radioactive decay series. If these equations are to be applied to the decay series, it is best to replace the q_i with N_i, where N_i signifies the number of atoms. This is necessary because of the change in atomic number and specific activity with each compartment. The number of atoms may be calculated using the foregoing equations. Then, if one wishes the activity of each radionuclide, the number of atoms is multiplied by the decay constant to yield the activity in disintegrations/unit time (Volume I, Chapter 3) Equation 27.

G. Analysis of Experimental Data

To this point in the discussions on kinetics of compartment systems, the relationships of q to time and parameters such as rate constants, input rates, weighting coefficients, and powers have been shown. It has been assumed that the numerical values of these parameters are known from previous information and applicable to the estimation of compartment inventories over time for some new case. Unfortunately, because of myriad of factors which modify the values of these parameters, one seldom has such values at his fingertips for credible application to specific problems. Therefore, it is common practice (and often a necessity) to estimate the desired parameters by introducing a tracer into a system of interest and directly measuring q(t). This involves the choice of an appropriate mathematical model and the determination of model parameters which will produce a reasonable simulation of the actual data.

The choice of a mathematical model that is appropriate may be a simple matter in some cases; or in others it may be a real challenge and perhaps the principal goal of making direct observations. For example, an animal might be whole body counted over time following an acute dose of tracer. If a time plot of log q yields data which follow a straight line, then one can probably assume that the exponential model

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$$\boxed{q} \xrightarrow{k}$$

provides an appropriate representation of the system. The animal is in reality more complex, but it is usually wise to adhere to the simplest model which provides an adequate simulation of the real system. In complex systems, observation of compartmental inventories over time following an acute dose may provide some insight into its structure, but it is rare that a system can be understood in detail from a single experiment. For example, several different model structures may provide a reasonable simulation of the true system. The best model analogue from a statistical curve fitting standpoint may not be the best structural simulation of the actual system.

Once a conceptual and mathematical model has been chosen for application to observations of a real system, the usual goal is to estimate the numerical values of the parameters inherent in the model. The most efficient way of doing this is likely to be a computerized curve-fitting routine in which parameters are adjusted until no other combination of parameter values produces a better fit to the data. Fit to the data is usually judged by the sums of the squared deviations between the model-fit and actual data points. Computerized curve-fitting procedures, while recommended if available, are somewhat beyond the intent of this text. It seems more reasonable for our purpose here to illustrate some simple curve-fitting procedures which can be performed with the ordinary desk calculator. Even if computer codes are available, it may save significant computer time to have initial estimates of the appropriate parameters. The methods the authors discuss may be described as "quick and dirty," in the sense that they can provide rapid estimates, but the estimates may not necessarily be those that provide the best fit from a statistical standpoint.

1. Retention Curves

Parameters that describe the rate at which a radionuclide is lost from a system are embodied in the various retention functions described earlier. Retention functions (Equation 90) may be determined by directly measuring q(t) following the acute introduction of tracer to the system of interest. The usual forms of retention functions are linear, exponential, multicomponent exponential, and power. The first indication of which model may best describe actual retention data can usually be obtained by plotting the data on linear, semilog, and log-log paper. Data following a reasonably straight line on linear paper could be considered linear; data plotting as a straight line on semilog paper would suggest the exponential model; and a straight line plot on log-log paper indicates the power function. Multicomponent exponential data frequently display a curve leading to a straight line at some point in time on semilog paper. However, a multicomponent exponential system may be more easily fit to a power function, particularly if there are three or more components and if the components are fairly evenly weighed.

The "quick and dirty" hand calculator method of fitting retention curves basically involves:

1. Linearization of the mathematical model
2. Least squares estimation of the parameters with linear regression.

The retention model

$$q(t) = q(o) - a\,t$$

requires no linearization since it is already in linear form. Thus, a least squares fit of a plot of q(t) vs. t yields an estimate of the slope of the curve which is a. Methods for accomplishing the least-squares fit are outlined in standard statistical texts.[97] The degree of confidence in the calculated value of a may be judged by the standard deviation of a or by the correlation coefficient.

In the case of the exponential model, one has

$$q(t) = q(o)\,e^{-\lambda t}$$

which may be linearized by taking the natural logarithm

$$\ln q(t) = \ln q(o) - \lambda t \qquad (164)$$

which is of the form

$$Y = Y(o) + a\,X$$

where X is the independent variable and Y is the dependent variable. Thus, the natural logarithm of each value of q is regressed against the corresponding values of t. The calculated slope provides the estimate of λ.

For the power function model,

$$q(t) = q(1)\,t^{p}$$

one may again linearize by taking logarithms,

$$\ln q(t) = \ln q(1) + p \ln t \qquad (165)$$

Thus in this case, ln q(t) is regressed against corresponding values of ln t. The slope of the regression provides the estimate of p.

The analysis of multicomponent exponential retention data is a bit more complicated than the three cases presented so far. Furthermore, it is subject to some bias. Let us illustrate the basic method by analyzing some example data. Suppose the following set of data was obtained

t	q(t)
0.5	46
1.0	25
1.5	16
2.0	11
2.5	12
3.0	8
4.0	8
5.0	7
6.0	8
7.0	6
8.0	6
10.0	5
12.0	4

A semilog plot of the data is made (Figure 29). A multicomponent model is suggested from the plot because of the apparent straight line behavior of the data for $3 < t \leq 12$, and the steeply curving section for $t < 3$. A least-squares fit of ln q(t) on t is made for the data over the range [illegible] linearity is apparent. The assumption is

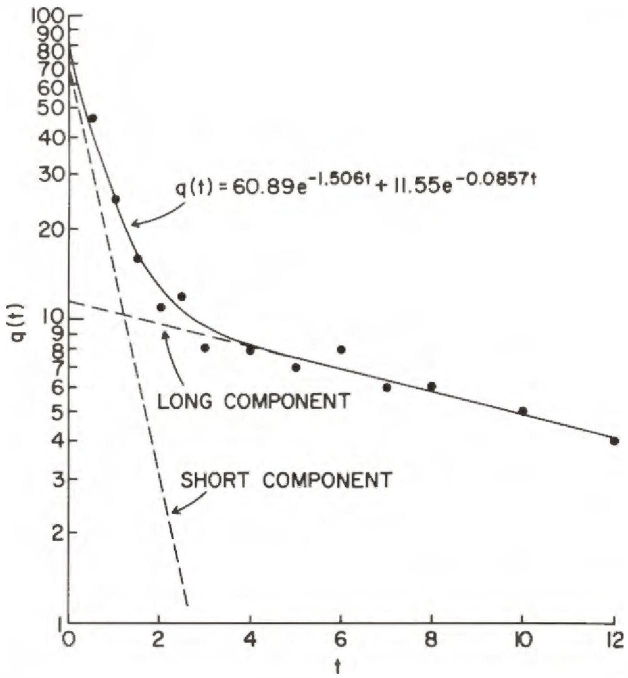


FIGURE 29. Fit of a two-component exponential model to a set of retention data.

made that steeper components of the retention curve do not significantly influence this straight section. Here is where some bias may enter because it is somewhat arbitrary where the cutoff point should be. Nevertheless, including all data for $t \geq 4$, one obtains a value for the slope of -0.0857 when ln q(t) is regressed against t. Further, the t(o) intercept is estimated from the regression equation as 2.447. Since 2.447 is ln Y(o), Y(o) is $e^{2.447}$ or 11.55. Thus, the equation for what is called the "long component" of the retention curve is

$$Y = 11.55\, e^{-0.0857\, t}$$

This is plotted as a dashed line in Figure 29.

The next step in the analysis is to subtract this "long component" from the data in the range $0 \leq t < 4$.

t	q(t)	$11.55\, e^{-0.0857\, t}$	$q(t) - 11.55\, e^{-0.0857\, t}$
0.5	46	11.1	34.9
1.0	25	10.6	14.4
1.5	16	10.2	5.8
2.0	11	9.7	1.3
2.5	12	9.3	2.7
3.0	8	8.9	−0.9

A plot of $\ln[q(t) - 11.55\, e^{-0.0857t}]$ vs. t suggests linearity, thus a two-component exponential model is indicated. Now, $\ln[q(t) - 11.55\, e^{-0.0857t}]$ is regressed against t. The negative value at t = 3.0 cannot be used since ln (−0.9) is undefined. This is another shortcoming of the procedure. The regression procedure yields a slope of −1.506 and a Y(o) value of 60.89. Therefore, the "short component" is estimated by

$$Y = 60.89\, e^{-1.506\, t}$$

which is also shown as a dashed line (Figure 29).

The function q(t) is estimated by the sum of the two components, namely

$$q(t) = 60.89\, e^{-1.506\, t} + 11.55\, e^{-0.0857\, t}$$

This is plotted as a solid line in Figure 29. The retention function, L(t), is normalized to q(o), where q(o) = 60.89 + 11.55 = 72.44.

$$L(t) = \frac{q(t)}{q(o)} = 0.84\, e^{-1.506\, t} + 0.16\, e^{-0.0857\, t}$$

The authors conclude that the two-component exponential model provides a reasonably good description of the data. However, it is entirely possible that a computerized curve-fitting routine may yield slightly different parameter values with a lower sum of squared deviations. The complexity of analysis and subjectivity of the method increase as additional components are added to the exponential model.

2. Buildup Curves

It is common to observe the buildup of a radionuclide in a compartment which is subject to a chronic input. If one has sufficiently good data for the compartment inventory over time, it is sometimes possible to estimate the key parameters in a model used to simulate the real system. Let us next examine a few such cases.

Assume a set of data in which q(o) is 0 and where q(t) appears to exponentially approach an equilibrium (eq) value (Figure 30). It would appear that this data set could be fit by a model of the form

$$q(t) = q(eq)\,(1 - e^{-\lambda t})$$

Since the data suggest a steady state for $t \geqslant 8$, one can estimate q(eq) by taking the mean of $q(t \geqslant 8)$. This yields a value of 41.4 for q(eq). Now again, one can linearize the model by the following manipulations:

$$q(t) = q(eq) - q(eq)\, e^{-\lambda t}$$

$$q(eq) - q(t) = q(eq)\, e^{-\lambda t}$$

$$\ln\left[q(eq) - q(t)\right] = \ln q(eq) - \lambda t \qquad (166)$$

Thus, a regression of $\ln[q(eq) - q(t)]$ on t yields an estimate of λ, where λ is the slope of the regression. If the data can be well-simulated by the above model, a plot of $\ln[q(eq) - q(t)]$ vs. t for values of $t < 8$ should exhibit reasonable linearity. A regression on these data yields a value of 0.387 for λ. Thus, the model describing the data is

$$q(t) = 41.4\,(1 - e^{-0.387\, t})$$

This is plotted as a solid line through the observed data (Figure 30). In this case, the model slightly underestimates the early observed data points. A somewhat better fit can be obtained for this example by constraining the regression line through the points ln 41.4, 0, and the mean values of $\ln[q(eq) - q(t)]$ and t. This yields an estimate of λ

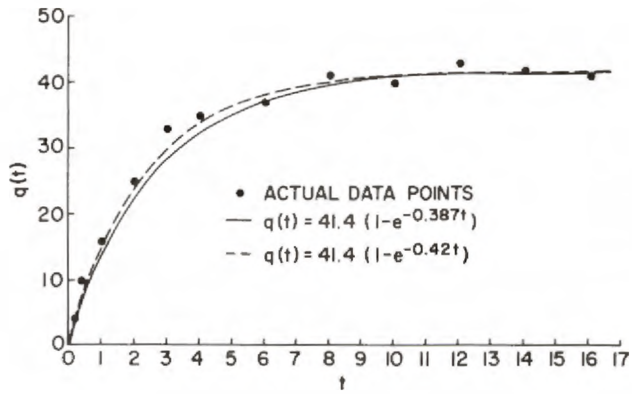


FIGURE 30. A hypothetical set of buildup data and an approximate simulation using the model $q(t) = q(eq)\,(1-e^{-\lambda t})$.

of 0.42 (see dashed line, Figure 30). As was the case with certain retention models, iterative computer codes can usually provide a better statistical fit than these approximate methods. Having an estimate of λ and q(eq), one can estimate the rate at which material is entering the compartment.

Since

$$q(eq) = \frac{R}{\lambda}$$

$$R = (41.4)\,(0.42\ t^{-1}) = 17.4/\text{unit time}$$

Note that in the previous example, data were available to directly estimate the equilibrium value, and this value was required in the curve-fitting method. What can be done if one wishes to fit the same model to a set of data which are not taken for a period sufficiently long to have reached steady state? This case is a bit more complicated, but not all that difficult provided the data are of reasonably high quality. This method involves estimating the derivative of the buildup curve from successive data points. The model is linearized as follows:

$$q(t) = q(eq)\,(1 - e^{-\lambda t})$$

$$\frac{dq(t)}{dt} = \lambda q(eq) e^{-\lambda t}$$

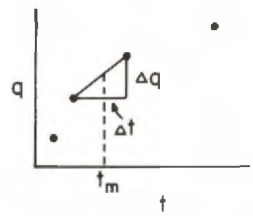
$$\ln\left[\frac{dq(t)}{dt}\right] = \ln\left[\lambda q(eq)\right] - \lambda t \qquad (167)$$

Successive data points may be used to estimate $\Delta q/\Delta t$ for specific values of t. From the Mean Value Theorem,

$$\frac{\Delta q}{\Delta t} \approx \frac{dq}{dt} \text{ at } t_m$$

where t_m = the mid point between the values of t used to determine Δt and Δt = a reasonably small value.

Graphically,



Therefore, for n data points, one may obtain n−1 estimates of $\Delta q/\Delta t$, each with a corresponding value of t_m. A regression analysis of $\ln(\Delta q/\Delta t)$ vs. t_m yields a slope (an estimate of λ) and a t = 0 intercept, $\ln[\lambda q(eq)]$. Since λ is estimated, one can resolve both q(eq) and R if desired.

This method becomes quite limited if the data show substantial scatter. For example, negative values of $\Delta q/\Delta t$ can result from scatter, and these are of no use in the regression since we are dealing with their logarithms. Various data-smoothing techniques may be used to avoid or reduce the occurrence of negative values, but this may lead to the loss of information.

A power function buildup curve is the result of a loss function of the form t^p. For chronic intake, a compartment exhibiting a power function loss will have a buildup function of the form,

$$q(t) = \frac{R}{p+1}\left(t^{p+1} - 1\right)$$

where p is negative, but $\neq -1$. Linearizing this equation, one obtains

$$\frac{dq(t)}{dt} = R\,t^p$$

$$\ln\left[\frac{dq(t)}{dt}\right] = \ln R + p \ln t \qquad (168)$$

Using the Mean Value Theorem concept as in the previous example, one has

$$\ln\left[\frac{\Delta q(t)}{\Delta t}\right] \approx \ln R + p \ln t_m$$

Thus, a regression of $\ln[\Delta q(t)/\Delta t]$ on $\ln t_m$ yields p as an estimate of the slope and ln R as an estimate of the t = 1 intercept. This approach was used to obtain a predictive equation for actual data collected by Millard on the buildup of radioactivity in growing barn swallows that were feeding on insects from a radioactive leaching pond at the Idaho National Engineering Laboratory (Figure 31).[97a]

The final example model the authors shall discuss is of the form

which is described by

$$q(t) = \frac{R(o)}{k-\lambda}\left(e^{-\lambda t} - e^{-kt}\right)$$

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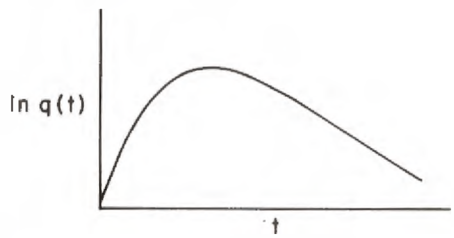
A plot of this equation is of the form



This model may be linearized as follows:

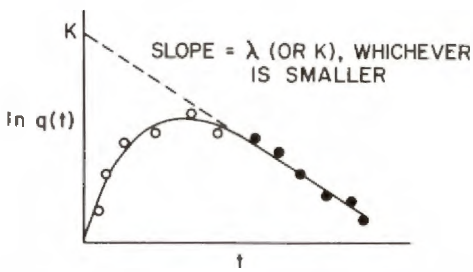
Letting $K = R(o)/(k-\lambda)$

$$q(t) = K\,e^{-\lambda t} - K\,e^{-kt}$$

$$K\,e^{-\lambda t} - q(t) = K\,e^{-kt}$$

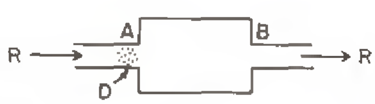
$$\ln\left[K\,e^{-\lambda t} - q(t)\right] = \ln K - kt \qquad (169)$$

In this case, it is necessary that $k > \lambda$ since K must be a positive value. If $\lambda > k$, then these symbols must be interchanged in Equation 168. Note that a regression of $\ln[K\,e^{-\lambda t} - q(t)]$ on t will yield an estimate of k as the slope. However, it is first necessary to estimate λ and K. This is done by fitting a regression line to the straight, downward-sloping portion of the plot of ln q(t) vs. t.



In this example, the solid data points shown could be used to estimate the slope and intercept K. This slope is either λ or k, whichever is smaller. Let us assume that $\lambda < k$. Next, for each value of t where one has a data point (open circles), we compute $K\,e^{-\lambda t}$. From each value of $K\,e^{-\lambda t}$ we subtract the corresponding q(t) value measured and take the natural logarithm of the resulting difference. Now we are ready to do the regression of $\ln[K\,e^{-\lambda t} - q(t)]$ on t to estimate the value of k.

This particular model and data fitting procedure is frequently applicable to problems involving the Stewart-Hamilton equation which is frequently encountered in tracer kinetics.[92] The following diagram illustrates this principle.



In this example, one has an open compartment, through which a tracee flows at rate

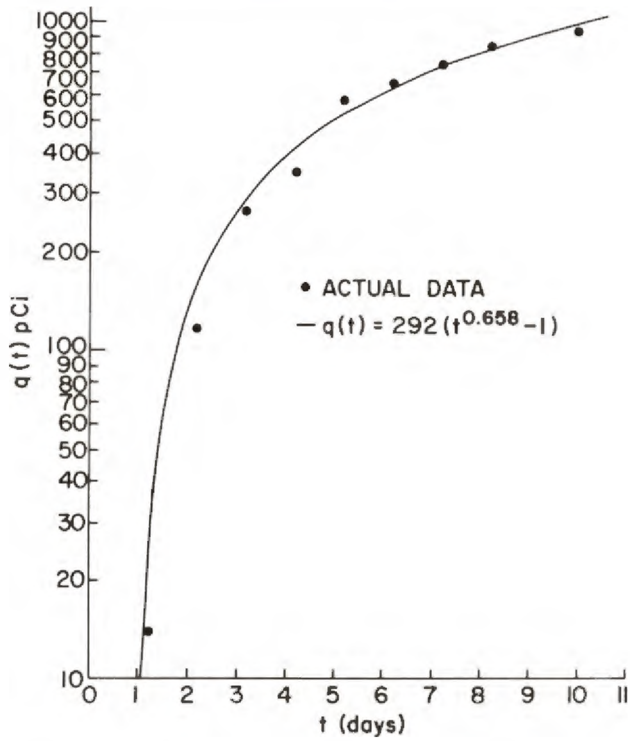


FIGURE 31. Fit of the power function model $q(t) = R(t^{p+1}-1)/(p+1)$ to data on buildup of radioactivity in growing barn swallows feeding on insects from a contaminated pond at the Idaho National Engineering Laboratory. Values for p and R were estimated as −0.342 and 192 pCi/day, respectively. (Courtesy of Mr. J. B. Millard.)

R. If an acute dose of tracer (D) is injected at point A, we can measure the specific activity (a) at point B through time. Then, we have the Stewart-Hamilton relationship

$$D = R \int_0^\infty a(t)\, dt \qquad (170)$$

This relationship permits an estimate of D, if R and a(t) are known, or an estimate of R, if D and a(t) are known. Frequently, a(t) is of the form K $(e^{-\lambda t} - e^{-kt})$, and if so, the parameters may be estimated by the previously described procedures.

IV. RADIONUCLIDE TRANSPORT MODELING

To this point in Volume II, Chapter 1, the authors have separately considered specific transport processes and some of the corresponding mathematical formulations, and some problems in kinetics of systems comprised of three or fewer compartments. The information was presented in such a way as to permit desk calculator computations for specific, comparatively simple systems. Such computations can be linked, in piecemeal fashion, to trace the movement of radionuclides from a source to and through a given ecosystem. However, the availability of high speed digital computers renders such piecemeal calculations rather obsolete for routine use. Furthermore, computers are the tool by which one can extend our modeling capabilities much further

than if one were limited to desk calculators. The purpose of this section is to discuss, in general terms, some modeling extensions made possible by computers, as well as the utility and limitations of models.

A. Utility of Transport Models

Radionuclide transport models seem to have two basic uses: prediction and understanding. These two basic uses are closely interrelated. No doubt the most widely recognized utility of radionuclide transport models is the prediction of radiation dose to plants, animals, and man resulting from releases of radioactive materials to the environment. The calculation of radiation dose is rather straightforward (usually), once the concentrations in tissues are estimated. However, owing to the basic complexity of ecosystems and their inherent processes, the estimation of tissue concentrations following an environmental release is seldom simple. If a release does occur, the most credible way to estimate tissue concentrations is direct sampling and measurement. However, many situations require the estimation of dose prior to or hopefully in the absence of a contaminating event. In certain cases, direct sampling and measurement may not be feasible because of cost, time-constraints, or other factors. Another example that requires a modeling approach is the after-the-fact estimation of dose from a prior event that was not followed up by direct sampling.

The other basic utility of models, namely that of understanding, has several components and ramifications. First, a transport model is basically a crude but semiquantitative representation of a real system. The formulation of a transport model requires some basic understanding of the structure and functional processes of the system. Thus, one must learn the system in order to model it. One can then test his understanding of the system by comparing model predictions to direct observations. Frequently, the radionuclide is strictly a tool to uncover knowledge about the system. Since the behavior of a radionuclide in a system is governed by its inherent structure and processes, the direct observation of radionuclide behavior after its introduction to a system must yield some information about it. Sometimes, radioactive tracers are purposely introduced to a system; other times investigators take advantage of natural- or man-caused events such as cosmogenic or nuclear weapons fallout.

Another important component of understanding involves organization of information. A system model, although usually imperfect and oversimplified, provides an excellent way to visualize the components of a system and their interactions. It provides an organizational tool for many separate pieces of information, and a means of testing our perception of how these pieces of information come together to form properties of the whole. Yet another utility of a model analogue of a real system is the possibility of theoretical manipulations and "what if" scenarios. One can quickly and cheaply do manipulations on a computer that would be totally impractical to carry out on real systems.

Models can seldom be exact replicas of systems, especially ecosystems. The components and processes are too numerous and complex to model in their entirety. Thus, one tries to model the major components and processes, and ignore those that play a minor role in the transport of energy and nutrients. The individual transport processes are usually described by the simplest formulations that provide reasonable simulation of the real system. Sensitivity analysis provides the computer modeler with a means of testing the importance of compartments, processes, and individual parameters on the final outcome or performance of the whole model. This is of great value to the investigator, because it provides a guide as to which components and processes require more study, and which can be ignored for the purpose at hand. Thus, models can provide a useful tool for the wise allocation of research efforts and other resources.

B. Limitations of Transport Models

Models potentially have great utility for prediction and understanding. However, they are not a panacea and can never replace the need for real data and creative thinking. The adage frequently heard these days, "garbage in, garbage out," is definitely true when applied to radionuclide transport models. Models are no better (and sometimes worse) than the thinking and data which go into them. In fact, too much reliance on a perhaps impressive and sophisticated, yet untested model could lead to misinterpretations and bad decisions.

As mentioned earlier, few real systems if any can be modeled to the extent that a high degree of realism is achieved. Workable models are those which provide a sufficient degree of realism and yet are computationally manageable. If a model is developed for a given ecosystem in a given time frame under a specified set of circumstances and validated with real data, then it is probably quite useful for that particular situation. However, the temptation to apply the model to other systems, time frames, or circumstances should be controlled. All distinct ecosystems exhibit differences in structure and function and any given system is expected to experience change with time and circumstance. Such structural and functional changes can be expected to alter the parameters describing system performance.[98]

Most radionuclide transport models involve numerous parameters, such as deposition velocities, resuspension factors, concentration ratios, assimilation fractions, retention rate constants, etc. Such parameters are not fundamental constants: they exhibit variation in response to time, place, and circumstance. Thus, errors and uncertainties in these parameters lead to corresponding error and uncertainty in model performance. Most transport models are "deterministic" in the sense that they employ specific parameter and input values and give specific numbers as output. Frequently, it is not possible to evaluate the possible error and uncertainty associated with the output values. Since there is uncertainty in several or many input and parameter values, the resulting error propagation in the final answer may be very large, possibly much larger than the error in any single input value. The authors see two possible ways to alleviate this problem. One is to make sure of the quality and applicability of the model, parameter values, and input data. This is easier said than done. The other approach is to develop a "stochastic" rather than deterministic model. A stochastic model is a probabilistic formulation in which parameters and input data are assigned frequency distributions rather than single numbers. In the calculations, the computer is allowed to choose values from each distribution of possible values according to the probability function. The calculation is repeated many times in order to generate a probability distribution of possible outcomes. The mean, median, and modal values can then be determined from the distribution, which in itself provides a measure of uncertainty for any particular outcome value.

In modeling applications to radiation dose estimation, uncertainty in parameter values is often handled by choosing those possible values which give the maximum credible dose. This is usually justified on the basis that it is better to overestimate the dose (and associated hazard) than to underestimate it. Of course, the stochastic procedure just discussed will also provide this type of information, with the added benefit of a probability statement for some maximum credible dose.

Few models have been formulated to account for seasonal changes in the model parameters. This can weaken the predictive capability of certain models considerably. Poikilothermic animals for example, are particularly subject to changes in metabolic rate with temperature. Thus, seasonal and diurnal temperature changes can drastically alter feeding rates, as well as excretion rates. Many other parameters may be affected by temperature as well as other environmental variables.

The inherent weaknesses of most models makes it difficult for most experienced

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scientists (and many laypeople for that matter) to accept their output. For this reason, and also for the purpose of improving accuracy, it is extremely important to validate or test models, especially those upon which important decisions may rest. Validation involves a comparison of actual data to values predicted in advance by the model. Good agreement between actual and predicted values, especially when observed over time and perhaps under varied circumstances, lends confidence to the model and its accuracy. On the other hand, a wide disparity may indicate problems with the model structure, parameter values, or input data. One thing about models; they can always be modified and usually improved upon.

C. Methods and Literature

As mentioned before, routine computations involving linked processes can usually be done most efficiently by computer. In addition, models with three or more linked compartments may well require solution by numerical approximation. Furthermore, even in the case of single-compartment models, certain input and/or loss functions may not have analytical solutions and numerical computations may, therefore, be required.

Most of the computational approaches to radionuclide transport models can be found in texts on numerical analysis.[99] These texts present standard numerical computation procedures called "algorithms". Such procedures yield nonexact solutions; however, completely adequate accuracy can be obtained by proper choice of the algorithm and appropriate computer programming. Most transport models require the solution of differential equations. Common numerical methods for solving the most frequently encountered types of differential equations include the Euler, Modified Euler, and Runge-Kutta algorithms. Of these, the Euler method is conceptually the simplest, but the Runge-Kutta is usually more accurate and practical because it can give sufficient accuracy with larger time steps and less computer time.[99]

Use of the algorithms mentioned above implies that the model is formulated, and that parameter values and input data are specified. The output is usually a time plot of compartment inventories, concentrations, or perhaps dose. A different approach is required when one wishes to estimate model parameter values from observed compartment inventories over time. One approach is to use an analogue computer to generate time plots of compartmental inventories with varied combinations of parameter values.[100] The parameter values may be sequentially adjusted by trial and error until the curves generated match the observed data with reasonable accuracy. The use of analogue computation for this is being replaced by digital computers which can basically perform the same operations and test each fit statistically. Thus, the computer can converge on a best fit. Another possible approach for linear, first-order differential equations is to write the set of equations which describe the inputs to and losses from each compartment of the model. Then, the observed data may be used to estimate the derivatives dq_i/dt and compartment inventories q_i for any number of points in time. For a system of n compartments, n equations may thus be generated with numerical values for dq_i/dt, q_i, and t. Matrix operations may then be employed to estimate values of the rate constants.

Many persons, faced with the task of modeling radionuclide transport in a complex system, elect to utilize one of the numerous existing computer codes. Researchers at Oak Ridge National Laboratory have compiled an index of documented computer codes which are applicable to environmental assessment of radionuclide releases.[101] These codes are indexed by name, transport processes, dosimetry, and computer language. Abstracts of each code are also provided. In September 1977, a workshop was held to evaluate the status of existing models on atmospheric, hydrologic, aquatic food chain, and terrestrial food chain transport.[102] This document should be consulted by

anyone seriously involved in transport modeling. Major weaknesses in existing transport models revealed at this workshop were the general lack of error evaluation and validation with actual data. Clearly, there is considerable room for modeling innovations, improvements, and testing.

REFERENCES

1. **Sutton, O. G.,** *Micrometeorology*, McGraw-Hill, New York, 1953.
2. **Slade, D. H., Ed.,** Meteorology and Atomic Energy 1968, U.S. AEC Rep. TID-24190, U.S. Atomic Energy Commission, Washington, D.C., 1968.

2a. **Engelmann, R. J.,** Meteorology and Atomic Energy 1968, U.S. AEC Rep. TID-24190, Slade, D. H., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1968, 208.

3. **Geiger, R.,** *The Climate Near the Ground*, (German transl.) 4th ed., Harvard University Press, Cambridge, 1965.
4. **Turner, D. B.,** Workbook of Atmospheric Dispersion Estimates (revised 1970), Rep. AP-26, Office of Air Programs, U.S. Environmental Protection Agency, Research Triangle Park, N.C., 1971.
5. **Smith, M., Ed.,** *Recommended Guide for the Prediction of the Dispersion of Airborne Effluents*, American Society of Mechanical Engineers, New York, 1968.
6. **Sutton, O. G.,** A theory of eddy diffusion in the atmosphere, *Proc. R. Soc. London Ser. A*, 135(826), 143, 1932.
7. **Basanquet, C. H. and Pearson, J. L.,** The spread of smoke and gases from chimneys, *Trans. Faraday Soc.*, 32(8), 1249, 1936.
8. **Pasquill, F.,** The estimation of the dispersion of windborne material, *Meteorol. Mag.*, 90(1063), 33, 1961.
9. **Gifford, F. A., Jr.,** Uses of routine meteorological observations for estimating atmospheric dispersion, *Nucl. Saf.*, 2(4), 47, 1961.
10. **Holland, J. Z.,** A Meteorological Survey of the Oak Ridge Area, U.S. AEC Rep. ORO-99, Oak Ridge Operations Office, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1953.
11. Geological Survey, The National Atlas of the United States of America, U.S. Department of Interior, Washington, D.C., 1970.
12. **List, R. J.,** Smithsonian Meteorological Tables, Publ. No. 4014, Miscellaneous Collections, Vol. 114, 6th ed. (revised), Smithsonian Institution, Washington, D.C., 1951.
13. **Engelmann, R. J. and Sehmel, G. A.,** Coordinators, Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants (1974), (ERDA Symp. Ser. 38), ERDA Rep. CONF-740921, Energy Research and Development Administration, Washington, D.C., 1976.
14. Panel on Radioactivity in the Marine Environment, *Radioactivity in the Marine Environment*, National Academy of Sciences, Washington, D.C., 1971.
15. **Gloyna, E. F. et al.,** Hydrologic transport of radionuclides, in Proc. Workshop on the Evaluation of Models Used for the Environmental Assessment of Radionuclide Releases, U.S. DOE Rep. CONF-770901, U.S. Department of Energy, Washington, D.C., 1978, 33.
16. U.S. Nuclear Regulatory Commission, Estimating Aquatic Dispersion of Effluents from Accidental and Routine Reactor Releases for the Purpose of Implementing Appendix I, Regulatory Guide 1.113 (Revision 1), U.S. Nuclear Regulatory Commission, Washington, D.C., 1977.
17. **Pritchard, D. W., Reid, R. O., Okubo, A., and Carter, H. H.,** Physical processes of water movement and mixing, in *Radioactivity in the Marine Environment*, Panel on Radioactivity in the Marine Environment, National Academy of Sciences, Washington, D.C., 1971, 90.
18. **Engelmann, R. J. and Slinn, W. G. N., Coordinators,** Precipitation Scavenging (1970), (AEC Symp. Ser. 22), U.S. AEC Rep. CONF-700601, U.S. Atomic Energy Commission, Washington, D.C., 1970.
19. **Bagnold, R. A.,** *The Physics of Blown Sand and Desert Dunes*, William Morrow, New York, 1942.
20. **McDonald, J. E.,** An aid to computation of terminal fall velocities of spheres, *J. Meteorol.*, 17(4), 463, 1960.
21. **McDonald, J. E.,** Rates of descent of fallout particles from thermonuclear explosions, *J. Meteorol.*, 17(3), 380, 1960.
22. **Kellogg, W. W., Rapp, R. R., and Greenfield, S. M.,** Close-in fallout, *J. Meteorol.*, 14(1), 1, 1957.
23. **Chamberlain, A. C.,** Aspects of the deposition of radioactive and other gases and particles, *Int. J. Air Pollution*, 3(1-3), 63, 1960.

BEST AVAILABLE COPY

24. **Markee, E. H., Jr. and Hawley, C. A., Jr.,** Controlled environmental radionuclide tests at the National Reactor Testing Station, in 8th AEC Air Cleaning Conf., U.S. AEC Rep. TID-7677, Kornegay, B. H., Jamison, D. K., and Morgan, J. H., Jr., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1964, 392.
25. Convair, Fission Product Field Release Test. I, Rep. NARF 59-32T (FZK-9-140; AFSWC-TR-59-44), U.S. Air Force Nuclear Aircraft Research Facility, 1959; as cited in **Slade, D. H., Ed.,** Meteorology and Atomic Energy 1968, U.S. AEC Rep. TID-24190, U.S. Atomic Energy Commission, Washington, D.C., 1968; *Nucl. Sci. Abstr.*, 14(2), 1715.
26. Convair, Fission Product Field Release Test. II, Rep. NARF-60-10T (FZK-9-149; AFSWC-TR-60-26), U.S. Air Force Nuclear Research Facility, 1960; as cited in **Slade, D. H., Ed.,** Meteorology and Atomic Energy 1968, U.S. AEC Rep. TID-24190, U.S. Atomic Energy Commission, Washington, D.C., 1968; *Nucl. Sci. Abstr.*, 15(3), 2905.
27. **Garland, J. A.,** Dry deposition of SO_2 and other gases, in Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants (1974), *(ERDA Symp. Ser.* 38) ERDA Rep. CONF-740921, Englemann, R. J. and Sehmel, G. A., Coordinators, Energy Research and Development Administration, Washington, D. C., 1976, 212.
28. **Craig, D. K., Klepper, B. L., and Buschbom, R. L.,** Deposition of various plutonium-compound aerosols onto plant foliage at very low wind velocities, in Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants (1974), *(ERDA Symp. Ser.* 38) ERDA Rep. CONF-740921, Engleman, R. J. and Sehmel, G. A., Coordinators, Energy Research and Development Administration, Washington, D.C., 1976, 244.
29. **Raynor, G. S.,** Experimental studies of pollen deposition to vegetated surfaces, in Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants (1974), *(ERDA Symp. Ser.* 38) ERDA Rep. CONF-740921, Englemann, R. J. and Sehmel, G. A., Coordinators, Energy Research and Development Administration, Washington, D. C., 1976, 264.
30. **Russell, I. J. and Choquette, C. E.,** Scale factors for foliar contamination by stratospheric sources of fission products in the New England area, in Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants (1974), *(ERDA Symp. Ser.* 38) ERDA Rep. CONF-740921, Englemann, R. J. and Sehmel, G. A., Coordinators, Energy Research and Development Administration, Washington, D. C., 1976, 302.
31. **Silker, W. B.,** Air to sea transfer of marine aerosol, in Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants (1974), *(ERDA Symp. Ser.* 38) ERDA Rep. CONF-740921, Engelmann, R. J. and Sehmel, G. A., Coordinators, Energy Research and Development Administration, Washington, D. C., 1976, 391.
32. **Millard, G. C., Fraley, L., Jr., and Markham, O. D.,** Seasonal variations in deposition and retention of cerium-141 and cesium-134 in *Sitanion hystrix* and *Artemisia tridentata,* in Ecological Studies on the Idaho National Engineering Laboratory Site 1978 Progress Report, U.S. DOE Rep. IDO-12087, Markham, O. D., Ed., Idaho Falls, 1978, 115.
33. **Sehmel, G. A. and Hodgson, W. H.,** Predicted dry deposition velocities, in Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants (1974), *(ERDA Symp. Ser.* 38), ERDA Rep. CONF-740921, Engelmann, R. J. and Sehmel, G. A., Coordinators, Energy Research and Development Administration, Washington, D. C., 1976, 399.
34. **Beilke, S.,** Laboratory investigations on washout of trace gases, in Precipitation Scavenging (1970), *(AEC Symp. Ser.* 22), AEC Rep. CONF-70061, Engelmann, R. J. and Slinn, W. G. N., Coordinators, U. S. Atomic Energy Commission, Washington, D. C., 1970, 261.
35. **Sood, S. K. and Jackson, M. R.,** Scavenging by snow and ice crystals, in Precipitation Scavenging (1970), *(AEC Symp. Ser.* 22) AEC Rep. CONF-700601, Englemann, R. J. and Slinn, W. G. N., Coordinators, U. S. Atomic Energy Commission, Washington, D. C., 1970, 121.
36. **Perkins, R. W., Thomas, C. W., Young, J. A., and Scott, B. C.,** In-cloud scavenging analysis from cosmogenic radionuclide measurements, in Precipitation Scavenging (1970), *(AEC Symp. Ser.* 22) AEC Rep. CONF-700601, Englemann, R. J. and Slinn, W. G. N., Coordinators, U. S. Atomic Energy Commission, Washington, D. C., 1970, 69.
37. **Engelmann, R. J.,** Scavenging prediction using ratios of concentrations in air and precipitation, in Precipitation Scavenging (1970), *(AEC Symp. Ser.* 22) AEC Rep. CONF-700601, Englemann, R. J. and Slinn, W. G. N., Coordinators, U. S. Atomic Energy Commission, Washington, D. C., 1970, 475.
38. **Chepil, W. S.,** Dynamics of wind erosion: I. Nature of movement of soil by wind, *Soil Sci.*, 60(4), 305, 1945.
39. **Chepil, W. S.,** Relation of wind erosion to wind-stable and dry clod structure of soil, *Soil Sci.*, 55(4), 275, 1943.
40. National Air Pollution Control Administration, Continuous Air Monitoring Projects, Rep. APTD 68-9, U.S. Department of Health, Education, and Welfare, U.S. Department of Energy, Washington, D.C., 1968.
41. **Slinn, W. G. N.,** Parameterizations for resuspension and for wet and dry deposition of particles and gases for use in radiation dose calculations, *Nucl. Saf.*, 19(2), 205, 1978.

42. **Skidmore, E. L.**, Wind Erosion Forces in the United States and their Use in Predicting Soil Loss, Agriculture Handbook, No. 346, U.S. Department of Agriculture, Washington, D.C., 1968.
43. **Skidmore, E. L.**, A wind erosion equation: development, application, and limitations, in Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants (1974), *(ERDA Symp. Ser.* 38) ERDA Rep. CONF-740921, Englemann, R. J. and Sehmel, G. A., Coordinators, Energy Research and Development Administration, Washington, D. C., 1976, 452.
44. **Healy, J. W. and Fuquay, J. J.**, Wind pickup of radioactive particles from the ground, *Proc. 2nd United Nations Int. Conf. Peaceful Uses of Atomic Energy*, 18, 291, 1958.
45. **Stewart, K.**, The resuspension of particulate material from surfaces, in *Surface Contamination*, Fish, B. R., Ed., Pergamon Press, New York, 1967, 63.
46. **Anspaugh, L. R., Shinn, J. H., Phelps, P. L., and Kennedy, N. C.**, Resuspension and redistribution of plutonium in soils, *Health Phys.*, 29(4), 571, 1975.
47. **Oksza-Chocimowski, G. V.**, Generalized Model of the Time-Dependent Weathering Half Life of the Resuspension Factor, U.S. EPA Rep. ORP/LV-77-4, U.S. Environmental Protection Agency, Las Vegas, Nev., 1977.
48. **Mills, M. T., Dahlman, R. C., and Olson, J. S.**, Ground Level Air Concentrations of Dust Particles Downwind from a Tailings Area During a Typical Windstorm, U.S. AEC Rep. ORNL-TM-4375, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1974.
49. **Glasstone, S. and Lewis, D.**, *Elements of Physical Chemistry*, 2nd ed., D Van Nostrand, New York, 1960.
50. **Duursma, E. K. and Gross, M. G.**, Marine sediments and radioactivity, in *Radioactivity in the Marine Environment*, Panel on Radioactivity in the Marine Environment, National Academy of Sciences, Washington, D.C., 1971, 147.
51. **Clanton, U.S., Bradley, W. F., and Gloyna, E. F.**, Radioactivity Transport in Water — Sorption and Release of Radionuclides by Sediments of the Guadalupe River, Tech. Rep. 6, Environmental Health Engineering Laboratory, University of Texas, Austin, 1964; U.S. AEC Rep. TID-22872, U.S. Atomic Energy Commission, Washington, D.C., 1964.
52. **Sorathesn, A., Bruscia, G., Tamura, T., and Struxness, E. G.**, Mineral and Sediment Affinity for Radionuclides, U.S. AEC Rep. CF-60-6-93, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1960.
53. **Millar, C. E., Turk, L. M., and Foth, H. D.**, *Fundamentals of Soil Science*, 4th ed., John Wiley & Sons, New York, 1965.
54. **Relyea, J. F. and Brown, D. A.**, Adsorption and diffusion of plutonium in soil, in Environmental Chemistry and Cycling Processes, *(DOE Symp. Ser., 45)*, DOE Rep. CONF-760429, Adriano, D. C. and Brisban, I. L., Jr., Eds., U.S. Department of Energy, Washington, D.C., 1978, 479.
55. **Comar, C. L., Wasserman, R. H., and Nold, M. M.**, Strontium-calcium discrimination factors in the rat, *Proc. Soc. Exp. Biol. Med.*, 92(4), 859, 1956.
56. **Fredriksson, L., Eriksson, B., Rasmuson, B., Gahne, B., Edvarson, K., and Low, K.**, Studies on soil-plant-animal interrelationships with respect to fission products, *Proc. 2nd United Nations Int. Conf. Peaceful Uses of Atomic Energy*, 18, 449, 1958.
57. **Comar, C. L. and Wasserman, R. H.**, Radioisotope absorption and methods of elimination; differential behavior of substances in metabolic pathways, in *A Symposium on Radioisotopes in the Biosphere*, Caldecott, R. S. and Snyder, L. A., Eds., University of Minnesota, Minneapolis, 1960, 526.
58. **Comar, C. L.**, Movement of fallout radionuclides through the biosphere and man, *Annu. Rev. Nucl. Sci.*, 15, 175, 1965.
59. **Fish, B. R., Ed.**, *Surface Contamination*, Pergamon Press, New York, 1967.
60. **Green, H. L. and Lane, W. R.**, *Particulate Clouds: Dusts, Smokes, and Mists*, E. & F. N. Spon, London, 1957.
61. International Commission on Radiological Protection, Report of Committee II on permissible dose for internal radiation (1959), *Health Phys.*, 3, 1, 1960.
62. **Kleiber, M.**, *The Fire of Life: An Introduction to Animal Energetics*, rev. ed., Krieger, Huntington, New York, 1975.
63. **Brody, S.**, *Bioenergetics and Growth*, Reinhold, New York, 1945.
64. **Krebs, C. J.**, *Ecology: The Experimental Analysis of Distribution and Abundance*, 2nd ed., Harper & Row, New York, 1978.
65. **French, N. R., Grant, W. E., Grodzinski, W., and Swift, D. M.**, Small mammal energetics in grassland ecosystems, *Ecol. Monogr.*, 46(2), 201, 1976.
66. **Odum, E. P.**, *Fundamentals of Ecology*, 3rd ed., W. B. Saunders, Philadelphia, 1971.
67. **Prosser, C. L.**, *Comparative Animal Physiology*, 3rd ed., W. B. Saunders, Philadelphia, 1973.
68. **Spector, W. S., Ed.**, *Handbook of Biological Data*, W. B. Saunders, Philadelphia, 1956.
69. **Hakonson, T. E., Gallegos, A. F., and Whicker, F. W.**, Cesium kinetics data for estimating food consumption rates of trout, *Health Phys.*, 29(2), 301, 1975.

70. Crossley, D. A., Jr., Consumption of vegetation by insects, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963.
71. Task Group on Lung Dynamics, Deposition and retention models for internal dosimetry of the human respiratory tract, *Health Phys.*, 12(2), 173, 1966.
72. Morgan, K. Z. and Turner, J. E., *Principles of Radiation Protection*, rev. ed., Krieger, Huntington, New York, 1973.
73. Holleman, D. F., Luick, J. R., and Whicker, F. W., Transfer of radiocesium from lichen to reindeer, *Health Phys.*, 21(5), 657, 1971.
74. Raabe, O. G., Some important considerations in use of power functions to describe clearance data, *Health Phys.*, 13(3), 293, 1967.
75. Gallegos, A. F. and Whicker, F. W., Radiocesium retention by rainbow trout as affected by temperature and weight, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P1, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 361.
76. Kitchings, T., DiGregorio, D., and Van Voris, P., A review of the ecological parameters of radionuclide turnover in vertebrate food chains, in *Radioecology and Energy Resources*, Cushing, C. E. et al., Eds., Dowden, Hutchinson & Ross, Stroudsburg, Pa., 1976, 304.
77. Hakonson, T. E. and Whicker F. W., Uptake and elimination of ^{134}Cs by mule deer, in Symp. Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington D.C., 1969, 616.
78. Schreckhise, R. G. and Whicker, F. W., A model for predicting strontium-90 levels in mule deer, in *Radioecology and Energy Resources*, Cushing, C. E. et al., Eds., Dowden, Hutchinson & Ross, Stroudsburg, Pa., 1976, 148.
79. Gist, C. S. and Whicker, F. W., Radioiodine uptake and retention by the mule deer thyroid, *J. Wildl. Manage.*, 35(3), 461, 1971.
80. Cadwell, L. L., Rangeland grasshopper foraging impact, Dissertation, Colorado State University, Fort Collins, 1973, *Diss. Abstrs.*, 35(2), 1112-B.
81. Reichle, D. E., Dunaway, P. B., and Nelson, D. J., Turnover and concentration of radionuclides in food chains, *Nucl. Saf.*, 11(1), 43, 1970.
82. Dahlman, R. C., Francis, C. W., and Tamura, T., Radiocesium cycling in vegetation and soil, in Mineral Cycling in Southeastern Ecosystems, *(ERDA Symp. Ser.* 36) ERDA Rep. CONF-740513, Howell F. G., Gentry, J. B., and Smith M. H., Eds., Energy Research and Development Administration, Washington, D. C., 1975, 462.
83. Heinemann, K., Vogt, K. J., and Angeletti, L., Deposition and biological half life of elemental iodine on grass and clover, in Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants (1974), *(ERDA Symp. Ser.* 38), ERDA Rep. CONF-740921, Elgelmann, R. J. and Sehmel, G. A., Coordinators, Energy Research And Development Administration, Washington, D. C., 1976, 136.
84. Russell, R. S., Interception and retention of airborne material on plants, *Health Phys.*, 11(12), 1305, 1965.
85. Witherspoon, J. P., Field studies of fallout retention by plants, in Survival of Food Crops and Livestock in the Event of Nuclear War, *(AEC Symp. Ser.* 24) AEC Rep. CONF-700909, Benson, D. W. and Sparrow, A. H., Eds., U. S. Atomic Energy Commission, Washington, D. C., 1971, 396.
86. Lovaas, A. I. and Johnson, B. E., Retention of near-in fallout by crops, in Survival of Food Crops and Livestock in the Event of Nuclear War, *(AEC Symp. Ser.* 24) AEC Rep. CONF-700909, Benson, D. W. and Sparrow, A. H., Eds., U. S. Atomic Energy Commission, Washington, D. C., 1971, 405.
87. Hanson, W. C., Fallout strontium-90 and cesium-137 in northern Alaskan ecosystems during 1959-1970, Dissertation, Colorado State University, Fort Collins, 1973, *Diss. Abstrs.*, 34(8), 4111-B.
88. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.109 (Rev. 1,) Washington, D.C., 1977.
89. U.S. Energy Research and Development Administration, Workshop on Environmental Research for Transuranic Elements, U.S. ERDA Rep. ERDA-76/134, U.S. Energy Research and Development Administration, Washington, D.C., 1975.
90. Polikarpov, G. G., *Radioecology of Aquatic Organisms*, (English transl.) Schultz, V. and Klement, A. W., Jr., Eds., North-Holland, Amsterdam, 1966.
91. Sheppard, C. W., *Basic Principles of the Tracer Method*, John Wiley & Sons, New York, 1962.
92. Shipley, R. A. and Clark, R. E., *Tracer Methods for In-Vivo Kinetics*, Academic Press, New York, 1972.
93. Rescigno, A. and Segre, G., *Drug and Tracer Kinetics* (English transl.), Ariotti, P., Ed., Blaisdell, Waltham, Mass., 1966.
94. Atkins, G. L., *Multicompartment Models for Biological Systems*, Methuen, London, 1969.
95. Thomson, W. T., *Laplace Transformation*, 2nd ed., Prentice-Hall, Englewood Cliffs, N.J., 1960.
96. Alldredge, A. W., Lipscomb, J. F., and Whicker, F. W., Forage intake rates of mule deer estimated with fallout cesium-137, *J. Wildl. Manage.*, 38(3), 508, 1974.
97. Snedecor, G. W. and Cochran, W. G., *Statistical Methods*, 6th ed., Iowa State University Press, Ames, 1967.

97a. **Millard, J. B.**, personal communication, Idaho National Engineering Laboratory, Idaho Falls, 1979.
98. **Patten, B. C. and Witkamp, M.**, Systems analysis of [134]cesium kinetics in terrestrial microcosms, *Ecology*, 48(5), 813, 1967.
99. **Burden, R. L., Faires, J. D., and Reynolds, A. C.**, *Numerical Analysis*, Prindle, Weber & Schmidt, Boston, 1978.
100. **Neel, R. B. and Olson, J. S.**, Use of Analog Computer for Simulating the Movement of Isotopes in Ecological Systems, U.S. AEC Rep. ORNL-3172, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1962.
101. **Hoffman, F. O., Miller, C. W., Shaeffer, D. L., Garten, C. T., Jr., Shor, R. W., and Ensminger, J. T.**, A Compilation of Documented Computer Codes Applicable to Environmental Assessment of Radioactivity Releases, U.S. ERDA Rep. ORNL/TM-5830, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1977.
102. Various authors, Proc. Workshop on the Evaluation of Models Used for The Environmental Assessment of Radionuclide Releases, U.S. DOE Rep. CONF-770901, U.S. Department of Energy, Washington, D.C., 1978.
103. **Van Dyne, G. M.**, personal communication, Colorado State University, Fort Collins, 1979.

ADDITIONAL READINGS

Aoyama, I. and Inoue, Y., A stochastic study on the concentration process of radioactive substances to aquatic organisms, *Health Phys.*, 26(2), 191, 1974.

Aoyama, I. and Inoue, Y., Estimation and evaluation of the radioactive contamination through a food web in an aquatic ecosystem. II. System analysis of the transfer of radionuclides through a food web, *J. Radiat. Res.*, 16(2), 132, 1975.

Belyaev, B. I., Exchange equations of radionuclides between marine organisms and the environment, in *Radiation and Chemical Ecology of Aquatic Organisms*, Polikarpov, G. G., Ed., Naukova Dumka, Kiev, 1972, 62; *Nucl. Sci. Abstr.*, 26(32), 53532.

Bernhard, M., Bruschi, A., and Moller, F., Use of compartmental models in radioecological laboratory studies, in Design of Radiotracer Experiments in Marine Biological Systems, Tech. Rep. Ser. No. 167, International Atomic Energy Agency, Vienna, 1975, 241.

Bittel, R., Contribution of a prediction model to the establishment of formulae for the discharge of radioactive effluent into water (in French), in Proc. Int. Symp. Radioecology Applied to the Protection of Man and His Environment, Rep. EUR-4800 d-f-i-e, Commission of the European Communities, Luxemburg, 1971, 977; *Nucl. Sci. Abstr.*, 27(3), 5281.

Booth, R. S., A systems analysis model for calculating radionuclide transport between receiving waters and bottom sediments, in *Environmental Toxicity of Aquatic Radionuclides: Models and Mechanisms*, Miller, M. W. and Stannard, J. N., Eds., Ann Arbor Science, Mich., 1976, 133.

Booth, R. S., Kaye, S. V., and Rohwer, P. S., A systems analysis methodology for predicting dose to man from a radioactively contaminated terrestrial environment, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 877.

Carlsson, S., A model for the movement and loss of ^{137}Cs in a small watershed, *Health Phys.*, 34(1), 33, 1978.

Conover, R. J. and Francis, V., The use of radioactive isotopes to measure the transfer of materials in aquatic food chains, *Mar. Biol.*, 18(4), 272, 1973.

Crossley, D. A., Jr. and Reichle, D. E., Analysis of transient behavior of radioisotopes in insect food chains, *BioScience*, 19(4), 341, 1969.

Crossley, D. A., Jr. and Gist, C. S., Use of radioisotopes in modeling soil microcommunities, in Proc. First Soil Microcommunities Conf., U.S. AEC Rep. CONF-711076, Dindal, D. L., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 258.

DiGregorio, D., Kitchings, T., and Van Voris, P., Radionuclide transfer in terrestrial animals, *Health Phys.* 34(1), 3, 1978.

Eberhardt, L. L., Modeling radionuclides and pesticides in food chains, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 894.

Eberhardt, L. L., Designing ecological studies of trace substances, in Environmental Chemistry and Cycling Processes, (*DOE Symp. Ser.* 45) U.S. DOE Rep. CONF-760429, Adriano, D.C., and Brisbin, I.L., Jr., Eds., U. S. Department of Energy, Washington, D. C., 1978, 8.

Eberhardt, L. L. and Nakatani, R. E., A postulated effect of growth on retention time of metabolites, *J. Fish. Res. Board Can.*, 25(3), 591, 1968.

Eberhardt, L. L. and Hanson, W. C., A simulation model for an arctic food chain, *Health Phys.*, 17(6), 793, 1969.

Eberhardt, L. L. and Nakatani, R. E., Modeling the behavior of radionuclides in some natural systems, in Symp. Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1969, 740.

Eberhardt, L. L., Gilbert, R. O., Hollister, H. L., and Thomas, J. M., Sampling for contaminants in ecological systems, *Environ. Sci. Technol.*, 10(9), 917, 1976.

Federov, A. F., Mathematical formulas for concentration coefficient study of radioactive material to sea biota, *Bull. Inst. Oceanogr.*, 63(1304), 1964.

Frittelli, L., Application of systems analysis methodology to the determination of the limiting radiological capacity of the area surrounding a nuclear facility, in Environmental Surveillance Around Nuclear Installations, Vol. 1, Publ. STI/PUB-353, International Atomic Energy Agency, Vienna, 1974, 425.

Garten, C. T., Jr., Gardner, R. H., and Dahlman, R. C., A compartment model of plutonium dynamics in a deciduous forest ecosystem, *Health Phys.*, 34(6), 611, 1978.

Goldberg, E. D., McCave, I. N., O'Brien, J. J., and Steele, J. H., Eds., *Marine Modeling. The Sea*, Vol. 6, John Wiley & Son, New York, 1977.

Gus'kova, V. N., Prokof'yev, O. N., Zasedatelev, A. A., Il'in, B. N., and Tikhonova, A. I., Dynamics of concentration of strontium-89 in water and carp tissues after a single contamination of a body of water (English transl.), *Hydrobiol. J.*, 7(1), 53, 1971.

Halfon, E. and Bargmann, R. E., System identification of radioisotope flows in aquatic microcosms, in *Radioecology and Energy Resources*, Cushing, C. E., Jr. et al., Eds., Dowden, Hutchinson & Ross, Stroudsburg, Pa., 1976, 184.

Hawthorne, H. A., Zellmer, S. D., Eberhardt, L. L., and Thomas, J. M., [137]Cesium cycling in a Utah dairy farm, *Health Phys.*, 30(6), 447, 1976.

Hoffman, G. R., The accumulation of cesium-137 by cryptogams in a *Liriodendron tulipifera* forest, *Bot. Gaz. (Chicago)*, 133(2), 107, 1972.

Ivanov, V. N. and Parchevskaya, D. S., The probable character of accumulation and effect of radionuclides in the marine environment (in Russian), *Dokl. Akad. Nauk SSSR*, 218(1), 215, 1974; (English transl. page 428).

Kahn, B., Measurement for modeling radionuclide transfer in the aquatic environment, in *Environmental Toxicity of Aquatic Radionuclides: Models and Mechanisms*, Miller, M. W. and Stannard, J. N., Eds., Ann Arbor Science, Mich., 1976, 165.

Kaye, S. V. and Nelson, D. J., Analysis of specific-activity concept as related to environmental concentration of radionuclides, *Nucl. Saf.*, 9(1), 53, 1968.

Kaye, S. V. and Ball, S. J., Systems analysis of a coupled compartment model for radionuclide transfer in a tropical environment, in Symp. Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1969, 731.

Kulikov, N. V., Bezel, V. S., and Ozhegov, L. N., Accumulation of radioisotopes by developing roe of tench *(Tinca tinca* L.) and perch *(Perca fluviatilis* L.), (in Russian), *Ekologiya*, 1(5), 73, 1970; (English transl. page 425).

Lu, A. H., Modeling of radionuclide migration from a low-level radioactive waste burial site, *Health Phys.*, 34(1), 39, 1978.

Martin, W. E. and Turner, F. B., Transfer of [89]Sr from plants to rabbits in a fallout field, *Health Phys.*, 12(5), 621, 1966.

Miller, C. W., Dunning, D. E., Jr., Etnier, E. L., Hoffman, F. O., Little, C. A., Meyer, H. R., Shaeffer, D. L., and Till, J. E., The Evaluation of Selected Predictive Models and Parameters for the Environmental Transport and Dosimetry of Radionuclides, U.S. DOE Rep. ORNL/TM-6663, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1979.

Murray, C. N. and Avogadro, A., Effect of a long-term release of plutonium and americium into an estuarine-coastal sea ecosystem. I. Development of an assessment methodology, *Health Phys.*, 36(5), 573, 1979.

Nihoul, J. C. J., Ed., *Modelling of Marine Systems*, Elsevier, New York, 1975.

O'Neill, R. V., Error analysis of ecological models, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P1, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 898.

O'Neil, R. V., Gerguson, N., and Watts, J. A., Bibliography of Mathematical Modeling in Ecology, Rep. EDFB/IBP-75/5, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1977.

Onishi, Y., Finite Element Models for Sediment and Contaminant Transport in Surface Waters. Transport of Sediments and Radionuclides in the Clinch River, U.S. ERDA Rep. BNWL-2227, Battelle Northwest Laboratory, Richland, Wash., 1977.

Onishi, Y., Mathematical Simulation of Sediment and Radionuclide Transport in the Columbia River, U.S. ERDA Rep. BNWL-2228, Battelle Northwest Laboratory, Richland, Wash., 1977.

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Ophel, I. L. et al., Aquatic food chain transport of radionuclides, in Proc. Workshop on the Evaluation of Models Used for the Environmental Assessment of Radionuclide Releases, U.S. DOE Rep. CONF-770901, U.S. Department of Energy, Washington, D.C., 1978, 73.

Parchevskaya, D. S., Scheme of statistical analysis and planning of experiment (in Russian), in *Marine Radioecology*, Polikarpov, G. G., Ed., Naukova Dumka, Kiev, 1970, 26; AEC-tr-7299 (English transl.), U.S. Atomic Energy Commission, Washington, D. C., 1970, 29.

Patzer, R. G., Concentration factors and transport models for radionuclides in aquatic environments. A literature report. Final report, Rep. PB-255097, Environmental Monitoring and Support Laboratory, U.S. Environmental Protection Agency, Las Vegas, 1976; Energy Research Abstracts 2-38387, U.S. Energy Research and Development Administration, Washington, D.C.

Piskunov, L. I., Statistical study of the accumulation of radioisotopes in aquatic organisms, *Gidrobiol. Zh.*, 6(5), 70, 1970; (English transl. page 58).

Piskunov, L. I., Quantitative aspects of the accumulation of radioisotopes by freshwater organisms, *Gidrobiol. Zh.*, 7(1), 64, 1971; (English transl. page 49).

Preston, A., Application of critical path analysis techniques to the assessment of environmental capacity and the control of environmental waste disposal, in Comparative Studies of Food and Environmental Contamination, Publ. STI/PUB/348, International Atomic Energy Agency, Vienna, 1974, 573.

Prokhorov, V. M. and Ginzburg, L. R., Modelling the process of migration of radionuclides in forest ecosystems and description of the model, *Ekologiya*, 2(5), 11, 1971; (English transl. page 396).

Reichle, D. E., Radioisotope turnover and energy flow in terrestrial isopod populations, *Ecology*, 48(3), 351, 1967.

Reichle, D. E., Measurement of elemental assimilation by animals from radioisotope retention patterns, *Ecology*, 50(6), 1102, 1969.

Rodionova, L. F. and Sukal'skaya, S. Ya., The accumulation of Ba-140 and La-140 by planktonic organisms from fresh water, *Gidrobiol. Zh.*, 5(6), 70, 1969; (English transl.).

Ruzic, I., Two-compartment model of radionuclide accumulation into marine organisms. I. Accumulation from a medium of constant activity, *Mar. Biol.*, 15(2), 105, 1972.

Sarma, T. P., Krishnamoorthy, T. M., and Sastry, V. N., An approach to the calculation of the allowable specific activities in marine fishes, *Health Phys.*, 20(1), 23, 1971.

Soldat, J. K. et al., Terrestrial food chain transport of radionuclides, in Proc. Workshop on the Evaluation of Models Used for the Environmental Assessment of Radionuclide Releases, U.S. DOE Rep. CONF-770901, U.S. Department of Energy, Washington, D.C., 1978, 85.

Svirezhev, Yu. M., Anokhin, V. L., and Tyuryukanov, A. N., Quantitative models in radiation biocoenology (in Russian), in *Methods of Radioecological Investigations*, Verkhovskaya, I. N., Ed., Atomizdat, Moscow, 1971, 207; *Nucl. Sci. Abstr.*, 26(6), 12255.

Turner, F. B., Uptake of fallout radionuclides by mammals and a stochastic simulation of the process, in Radioactive Fallout from Nuclear Weapons Tests, (*AEC Symp. Ser.* 5) U.S. AEC Rep. CONF-765, Klement, A. W., Jr., Ed., U. S. Atomic Energy Commission, Washington, D.C., 1965, 800.

Vanderploeg, H. A. and Booth, R. S., Interpretation of biological-rate coefficients derived from radionuclide content, radionuclide concentration and specific activity experiments, *Health Phys.*, 31(1), 57, 1976.

Vanderploeg, H. A., Booth, R. S., and Clark, F. H., A specific activity and concentration model applied to cesium-137 movement in a eutrophic lake, in *Radioecology and Energy Resources*, Cushing, C. E., Jr. et al., Eds., Dowden, Hutchinson & Ross, Stroudsburg, Pa., 1976, 164.

Van Winkle, W., Modelling techniques for predicting long-term consequences of the effects of radiation on natural aquatic populations and ecosystems, in Methodology for Assessing Impacts of Radioactivity on Aquatic Ecosystems, Tech. Rep. Ser. No. 190, International Atomic Energy Agency, Vienna, 1979, 119.

Various authors, Proc. Workshop on the Evaluation of Models Used for the Environmental Assessment of Radionuclide Releases, U.S. DOE Rep. CONF-770901, U.S. Department of Energy, Washington, D.C., 1978.

Wallis, I. G., Modelling techniques for predicting the long-term consequences of radiation on natural aquatic populations, in Methodology for Assessing Impacts of Radioactivity on Aquatic Ecosystems, Tech. Rep. Ser. No. 190, International Atomic Energy Agency, Vienna, 1979, 97.

Watts, J. R. and Murphy, C. E., Jr., Assessment of potential radiation dose to man from an acute tritium release into a forest ecosystem, *Health Phys.* 35(2), 287, 1978.

Webb, G. A. M. and Morley, F., Model for the evaluation of the deep ocean disposal of radioactive waste, in Proc. 3rd Int. Congr. Int. Radiation Protection Association, U.S. AEC Rep. CONF-730907-P1, U.S. Atomic Energy Commission, Washington, D.C., 1974, 313.

White, G. C., Adams, L. W., and Bookhout, T. A., Simulation model of tritium kinetics in a freshwater marsh, *Health Phys.*, 34(1), 45, 1978.

Yegorov, V. N. and Kulebakina, L. G., Mathematical model of Sr^{90} exchange between *Cystoseira* and marine water (in Russian), in *Radioecology of Water Organisms*, Vol. 2, Andrushaitis, G. P., Ed., Zinatne, Riga, 1973, 281; AEC-tr-7606 (English transl.), Atomic Energy Commission, Washington, D.C., 1973, 167; *Nucl. Sci. Abstr.*, 30(8), 21148.

Zuccaro Labellarte, G., A distribution model for radioactive and other persistent pollutants in the environment and in the food chain, in Comparative Studies of Food and Environmental Contamination, Publ. STI/PUB/348, International Atomic Energy Agency, Vienna, 1974, 585.

Chapter 2

EFFECTS OF IONIZING RADIATION ON SPECIES, POPULATIONS, COMMUNITIES, AND ECOSYSTEMS

I. INTRODUCTION

A great deal has been published on the effects of ionizing radiation on plants and animals and the mechanisms involved, particularly from the molecular to organism levels of biological organization. The literature contains general books on the subject such as those of Bacq and Alexander,[1] Casarett,[2] and Arena.[3] In addition, comprehensive reviews of major importance have been prepared, including the so-called BEIR[4] and UNSCEAR[5] reports. Bibliographies of primary importance are those of Pierce,[6] Ingram[7] and a combined index to these prepared by Bost and co-workers.[8,8a,8b] Relatively recently a bibliography specifically on effects of low-level radiation was published.[9] Although much of the research on effects of ionizing radiation has utilized domesticated plants and laboratory animals, considerable effort has been expended, particularly in the last two decades, on plants and animals in the natural environment.

Most early studies on "wild" animals involved observation in the laboratory following acute irradiation of single organisms or populations. Investigators were concerned that observations on typical laboratory animals were not relevant to feral species; consequently, they conducted laboratory investigations on some of these species. Recognizing that radiation response in the laboratory could differ from the response in the natural environment, investigations were made more relevant by releasing irradiated wild animals into natural habitats. As an ultimate objective of radiation ecologists was to investigate the effects of ionizing radiation at higher levels of integration, efforts were made to irradiate populations, communities, and ecosystems in place.

The complexities associated with such investigations are formidable. A considerably greater degree of complexity is involved when one considers the effects of ionizing radiation (or any other stress) at the population or community levels as compared to the organism level, particularly when investigations are conducted in the field. At the community level, direct effects of radiation on individuals become intertwined with indirect effects of multiple interactions and secondary effects. In a natural community, niche space is available to populations only under the condition that their existence within a certain space and at a certain density is compatible with conditions imposed by the abiotic environment and by other members of the living community. Regulation of a plant or animal population is achieved by relationships of space, nutrient supply, available sunlight, water, and a host of other factors, all of which are affected by other populations of the biotic community. The result then is that changes observed in a community following irradiation are caused not only by ionizing radiation per se, but also by interactions and secondary effects which result from the inherent nature of that community and its supportive elements. Without ancillary information, the relative importance of factors responsible for observed changes in an irradiated community may be obscure. These complexities and resulting high costs of experimentation have restricted the number and magnitude of field investigations.

As our objectives in this chapter are to discuss the impact of ionizing radiation at the population and community levels, we have cited only a few of the available references on effects of irradiation on "wild" organisms and then only to illustrate a point under discussion. Further, we have refrained from discussing differences in those results apparently resulting from shortcomings in experimental design and statistical evaluation. We cannot emphasize too strongly the need for proper experimental design

and data evaluation in future studies. In spite of some conflicting experimental results appearing in the literature, reasonable generalities as to the effects of ionizing radiation on populations and communities at doses currently existing or those of the foreseeable future can be drawn.

II. BIOLOGICAL EFFECTS OF IONIZING RADIATION: A BRIEF REVIEW

In order to provide some foundation for our discussions to follow, the authors will briefly discuss a few of the better-established concepts of radiobiology, especially as they relate to an understanding of ionizing radiation as a potential stress on populations and communities. Before they discuss the kinds of biological effects that have been observed, it is important to appreciate some of the important caveats of radiobiology. The basic caveat is that the biological response to radiation is dependent on factors associated with the radiation, the biological system, and the environment of the system. Let us next examine these ideas in more detail.

A. Radiation and How it Affects the Biological Response

To say that something has been exposed to radiation tells us practically nothing. Ionizing radiation is part of the environment of all living things and thus all life is continuously exposed to it. To evaluate the biological significance of radiation exposure it is at the least, necessary to know:

1. The total exposure and absorbed dose
2. The length of the exposure
3. The exposure rate or exposure fractionation
4. The type and energy of radiation
5. The rate at which the ionizing particles deposit energy (the linear energy transfer, LET)
6. The spatial distribution of dose

It is necessary to know the total exposure because if it is small (say relative to background) the biological consequences may be negligible; if very high, the consequences may be catastrophic. Between the two extremes, the entire range of possible effects or risk of effects is encountered. In addition to the exposure (the amount of radiation exposed to), it is important to quantify the absorbed dose (the amount of energy actually absorbed by the tissues). The relation between exposure and dose is dependent upon the types and energies of the radiation, as well as the type of biological tissue (see Volume I, Chapter 3). The quantitative relation between dose and effect is known as the dose-response curve. This may be linear or nonlinear, and may or may not have a threshold. Quantification or dose-response at low doses is presently one of the great challenges in radiobiology.

It is also important to know the length of the exposure, because this affects the exposure rate. The average exposure rate is the total exposure divided by the exposure time. The longer it takes to deliver a given total exposure, the less effect the radiation will have on the biological system. Conversely, the higher the exposure rate, the greater is the biological effect for a given total exposure. In certain cases, the exposure rate may be more important than total exposure in determining effect. A fundamental reason for the dose rate effect is the capability for biological repair of radiation-induced damage. Repair processes occur at all levels of biological organization, but fundamentally, damage and subsequent repair occur at the molecular and cellular levels. The lower the rate of dose delivery, or in the case of fractionated exposures, the longer the

period between exposures, the greater the opportunity for repair and recovery. The capability for repair is inversely related to the amount of damage.

The type and energy of radiation affect the biological response. For the same amount and rate of energy absorption in tissues, different types and energies of radiation may exhibit considerably different effectiveness in producing damage. The form and energy of radiation affect the LET. The LET measures the density of energy loss as an ionizing particle or photon traverses the biological material in question. It has the units of energy dissipated per unit length of track (KeV/μm, for example). In general, the greater the LET the greater is the damage at the molecular level. For example, a high LET particle may have a much greater chance of breaking chromosome strands than a low LET particle. As the LET continues to increase, a point is ultimately reached where the biological damage per unit of dose begins to diminish. This occurs because only so much damage can be done within a given region and after that point is reached, additional energy dissipation is "wasted," that is, it causes no additional damage.

The spatial distribution of absorbed dose significantly affects biological response, and this has been one of the more vigorously debated topics of radiobiology in recent years. The problem has several aspects. First, since different tissues display varied radiosensitivity, it is important to know which organs and tissues are receiving the greatest doses. If the dose is delivered by an internally deposited radionuclide, this question is of importance because the chemical properties of the radionuclide can significantly alter the sites of deposition. Some radionuclides are comparatively insoluble and mainly irradiate the GI tract if ingested. Isotopes of iodine will primarily irradiate the thyroid, other nuclides will lodge in and primarily expose bone tissue. If the source of radiation is external to the organism, the distribution of dose is dependent on the type and energy of the radiation and a host of other factors.

Another important aspect of particular significance to alpha emitters of low solubility is the formation of "hot spots". For example, at two extremes, a given quantity of ^{239}Pu could be uniformly distributed as single atoms throughout a given mass of lung tissue, or the plutonium atoms could all be constituents of a single particle, lodged somewhere within the same lung mass. The total dose, averaged over the entire lung would be the same in each case. However, in the case of the single particle, the dose to the small quantity of tissue immediately surrounding the particle would be very high, but the remainder of the lung (the vast majority of the tissue) would be unirradiated. In the case of the single atoms, the dose would be much lower on the average than around the hot spot, but many more cells would be at risk. There has been debate as to which situation leads to the greater biological risk, but most scientific evidence favors the dispersed dose as producing the greater risk.

B. Biological Factors and Radiation Response

Fundamental characteristics of the biological system can markedly affect the response of the system to radiation exposure. Characteristics of importance can be classified at the molecular and cellular level, on the basis of morphological organization at the tissue level, with regard to physiological and biochemical factors, and on the basis of organism traits. Some of the more important biological characteristics affecting the radiation response include:

1. Chromosome number, volume, and duplication
2. Length of the mitotic cycle
3. Percentage of cells dividing
4. Stage of the nuclear cycle
5. Type of cell or tissue

6. Stage of cell differentiation
7. Stature of organism
8. Age of organism
9. Stage of growth cycle
10. Nutritional condition
11. Concentrations of sensitizing or protective substances
12. Species

The fundamental "target" or structure where most consequential radiation damage occurs in biological systems is the chromosome. Radiation can break chromosomes and this can lead to subsequent effects such as genetic change, loss of cellular function, inability of cells to divide, and abnormal cells. Since the chromosome is a critical structure, it might be expected that radiosensitivity is related to their size, number, and extent of duplication. If a given amount of genetic information is contained in a few, large chromosomes, a certain dose is likely to cause a break that could lead to much loss of information. The same dose, given to the same amount of genetic information apportioned among many small chromosomes is less likely to cause the loss of significant information. Furthermore, large chromosomes are likely to absorb more energy per unit of exposure than small chromosomes, thus the larger ones are more likely to sustain damage. If there is redundant genetic information, as is the case with polyploid organisms, there is less chance of losing vital information, so polyploidy confers some degree of resistance.

The degree and rate of cell division have a great deal of influence on radiosensitivity. First, many cells are more sensitive to radiation when they are actively dividing and proliferating. If structure and/or function are dependent upon cell division, radiation may impair that structure and/or function by reducing the ability of cells to divide. Even if such cells are not killed outright and continue to function, a loss of mitotic capability may have serious consequences. Some tissues, such as nerve fibers and muscle, are considered radioresistant because their mitotic activity is low. In contrast, stem cells of the intestine are sensitive because they divide rapidly and continually. Furthermore, they are of extreme importance to the maintenance of integrity and function of the intestine. As another example, plant growth is dependent on the mitotic activity of the meristematic tissues. Growth may be inhibited by irradiation of these tissues at much lower doses than would be necessary to kill the mature, nondividing tissues of the plant. With chronic irradiation, there are cases where somewhat the opposite appears true. That is, temporarily dormant cells may seem more sensitive than actively dividing cells. This has been observed in plants and explained by the fact that the dormant cells may accumulate a greater average dose and have less capability for repair than active cells. The damage becomes manifest when it is time for the dormant cells to become active.

Stature (size) appears to affect the radiosensitivity of many organisms. This is particularly true in the plant kingdom, where in general, the larger the organism the more sensitive it is to irradiation. Reasons for this may be found in terms of subcellular characteristics, physiological requirements, and complexity or degree of specialization. In general, allowing some exceptions, phylogenetically primitive organisms are more resistant to irradiation than comparatively advanced forms.

Age or stage of development is certainly an important determinant of radiosensitivity, especially in certain groups of organisms. Some insects for example, can withstand over 20,000 rad (acute) as adults, but exhibit lethality at less than 2000 rad in early larval stages. Mammals are considerably more radiosensitive in utero than as adults. Age effects can usually be explained on the basis of differences in cell division characteristics and cell differentiation.

Health and nutrition can affect the ability of organisms to withstand most forms of stress, and this is certainly true in the case of radiation exposure. The repair capacity of healthy, nutritionally adequate organisms can be expected to be superior to weakened individuals. Among members of the same population it would not be surprising to find some individuals that could survive say, 500 rad, while others may not survive 300 rad. This is why parameters such LD_{50} (lethal dose to 50% of the individuals) have been developed. Of course, general health and nutrition are not the only factors in the determination of radiosensitivity among individuals of the same population. Chemical substances in the body, as well as other inherent or environmental factors can also modify the response.

C. Environmental Factors and Radiation Response

A host of abiotic and biotic features in the environment of a biological system can modify the response of that system to radiation exposure. While the authors believe this statement is true, there is less evidence to back it up than comparable statements about radiation and biological characteristics. Nevertheless, important environmental factors certainly include:

1. Season (as it affects other environmental variables)
2. Temperature
3. Moisture
4. Daylength
5. Sunlight
6. Environmental chemicals
7. Competition
8. Parasitism, predation, and food selection

Season, or time of year, affects a large number of other variables, and a combination of these can alter such things as the physiological state of plants and animals. In turn, physiological state can modify radiosensitivity. For instance, plant communities are more sensitive to acute irradiation during active growth phases than in dormancy. Hibernating mammals show little response to certain exposure ranges until they come out of hibernation. Seasonally and diurnally related variables such as temperature, moisture, and light can affect hormone concentration and behavior patterns of many organisms, which in turn, can modify radiosensitivity, or perhaps the potential to become exposed to radioactivity.

The environment has practically no limit, it often seems, to the number and intensity of possible physical, chemical, and biological stresses that can be found. Although little work has been done in this area, the authors are confident that radiation and other stresses can act synergistically on organisms. In most cases, one would expect that a separate stress would heighten the magnitude of the response to a given radiation exposure. However, it is also possible that adaptation to other forms of stress may equip some organisms to better tolerate radiation. A possible example of the latter is the exceptional radioresistance of plant communities which have evolved in harsh or extreme climates.

There are many lucid examples of the influence of inter- and intraspecific competition on radiation response in both plants and animals. For example, in irradiated plant communities it is commonly observed that comparatively radioresistant plants can thrive under increased radiation exposure. This is usually not a stimulatory response to irradiation, but rather an opportunistic response to reduced competition from more sensitive species that have regressed. Highly territorial animals, to extract an example from the animal kingdom, have been shown to have a significantly reduced chance of surviving a radiation [illegible] if [illegible] fense of a territory.

Table 1
TYPES OF RADIATION EFFECTS BY LEVEL OF ORGANIZATION AND GENERAL ACUTE DOSE LEVEL RANGE WHERE EFFECT MAY BE SIGNIFICANT

Level of organization	Type of effect	Qualitative acute dose level: Low (<1 rad)	High (>100 rad)
Molecular	DNA strand breaks	←	→
	Chemical toxins		←→
	Biochemical lesions	←	→
Cellular	Mitotic delay	←→	
	Mitotic death	←	→
	Carcinogenesis	←	→
Tissue/organ	Necrosis, lesions		←→
	Loss of function		←→
	Tumor appearance	←	→
Organism	Radiation sickness		←→
	Acute lethality		←→
	Cancer	←	→
	Genetic lesions	←	→
	Shortened life span	←	→
Population	Decreased natality	←	→
	Increased mortality		←→
	Decreased numbers	←	→
Community	Reduced productivity	←	→
	Reduced biomass		←→
	Reduced diversity		←→
	Altered composition		←→
Ecosystem	Reduced energy fixation	←	→
	Nutrient loss		←→
	Soil erosion		←→

Other biological interactions, such as parasitism, predation, and food selection may affect the radiation response. Conversely, the radiation response may alter interactions such as parasitism, predation and feeding pattern. Radiation-stressed individuals may be more susceptible to parasites and predation, and strangely, to consumption. The latter was observed at Brookhaven National Laboratory, Upton, Long Island, N.Y. by Woodwell, who noted that aphids preferentially utilized irradiated oak leaves. These sorts of phenomena point to the intricacies of ecosystems as well as to the difficulty of interpreting the response of irradiated organisms in their natural environments.

D. Types of Radiobiological Effects

Having just considered some of the more important factors which influence radiobiological effects, let us next consider some of the major kinds of effects. The classic effects and sets of radiation induced symptoms, called "syndromes", are described in basic radiobiology texts.[1,2] Rather than reiterate these descriptions in detail, they are simply listed in Table 1. The listing is broken down according to the level of biological organization, with qualitative indication of the dose levels at which the effects might be observed.

The types of effects listed in Table 1 are not independent; virtually all may be traced back to changes at prior levels of organization. The fundamental change at the molecular level which is of greatest importance for all but extremely high dose levels (>10,000 rad), is strand breakage of DNA (deoxyribonucleic acid). This phenomenon occurs at all dosage levels and leads to most genetic and somatic effects of concern. Of course,

the probability and extent of DNA strand breakage is dependent on dose and LET. Other biochemical lesions and chemical toxins such as free radicals and hydrogen peroxide are produced by ionizing radiation, but the significance of this is probably not manifest unless very high doses are encountered.

Some low dose effects, such as genetic change, cancer, and premature aging are probabilistic in their occurrence. They may or may not occur. The probability of occurrence is generally assumed to increase with dose. Of course there is some probability of these effects in the absence of radiation exposure, as radiation is not their only cause.

Table 1 only lists some general effects, but it should be noted that there is a long story associated with each, and further details should be sought by the serious reader. For example, acute lethality at the organism level has several aspects. In mammals, for example, there are several dose-dependent syndromes that cause fairly rapid mortality. At acute whole body doses of around 300 to 600 rad, mammals will encounter the hematopoetic syndrome and likely perish within 2 to 4 weeks because of certain blood changes which reduce the body's ability to fight bacterial infections. At doses of around 1000 rad or greater the GI tract becomes ulcerated, and the loss of fluids, electrolytes, and infection generally cause mortality within 1 week or less. Very high doses, say tens of kilorads, cause the hematopoetic and GI syndromes, but these do not have time to develop because mortality occurs too rapidly (< 1 day) owing to central nervous system (CNS) damage.

Effects of noticeable consequence at the population, community, and ecosystem levels require rather high doses of radiation. Even though subcellular and cellular lesions may occur at low doses, they are not manifest in the measureable attributes of populations or communities. A few abnormal cells or organisms will likely not survive to perpetuate the abnormality. Healthy, unaffected organisms will quickly fill voids or spaces made available through mortality of affected individuals, and thus will dominate. Only with doses sufficient to cause substantial reduction in natality and probably also considerable mortality, can dramatic changes in populations and communities be seen. Intermediate level doses may cause slight reductions in community productivity by reducing normal growth rates of sensitive plant species without causing basic alterations in community structure.

There is a fundamental difference in the way that we, as humans, view radiation effects or risk of effects in individual people, as compared to populations of other species or natural communities. In the case of people, our value system is strongly focused upon the individual. However small the risk from added radiation might be, people loathe to accept such risk because it may impinge upon them in a personal way. In terms of most nonhuman populations and natural communities however, concern at the individual level is diminished. A few trees are of little importance, so long as the healthy forest persists. This is no doubt a fundamental reason why there are very rigid standards for radiation exposure of humans, but no such standards for other species.

Genetic effects are a good example of the double standard we have for humans vs. other populations. Genetic changes are basically chromosome aberations incurred in the germ cells and passed to offspring. Since the vast majority of these mutations are likely to be harmful to the offspring, they are usually selected out of the population rather than persist. We consider "good" the selection and disappearance of harmful genetic information in nonhuman populations. Quite the opposite view is held for the human population, not because bad genetic information is desired, but rather because the selection process may be a painful experience at the individual level.

E. Pertinent Literature

Individual articles on wild species, populations, and communities are scattered

throughout a variety of professional periodicals and other communication outlets. However, one is fortunate that much of the literature on effects of ionizing radiation has been summarized for specific groups of organisms or populations and communities: protozoa,[10] brine shrimp,[11] insects,[12] development of amphibians,[13] reptiles,[14] and wild birds.[15] The authors would be remiss not to mention the excellent bibliography on effects on plants by Sparrow, et al.[16] and the bibliographies on insects by Bingelli that are listed in Appendix A.

The reader's attention should also be called to some extensive reviews on effects of ionizing radiation on terrestrial and aquatic organisms, populations, and communities. Whicker and Fraley[17] discussed plant communities, Turner[18] reviewed primarily terrestrial animal populations, and Blaylock and Trabalka[19] emphasized aquatic organisms at species and population levels. Several other reviews or books on aquatic organisms have also been prepared.[20-28]

Other major works are available on genetic effects,[29-32] late somatic effects,[33] reproduction,[34-36] immune mechanisms,[37] neural function and behavior,[38] premature aging and lifespan shortening[39], the fetal and juvenile mammal,[40] plant seeds[41] comparative radiosensitivity,[42-43] and general aspects of radiation injury.[44]

III. METHODS OF INVESTIGATING EFFECTS ON POPULATIONS, COMMUNITIES, AND ECOSYSTEMS

A. Source of Ionizing Radiation

Exposure of organisms to ionizing radiation can result from various sources or a combination of them, such as cosmic rays, primordial radionuclides, and artificial radionuclides resulting from the activities of man. The exposure may be external, internal, or both, depending on the source of ionizing radiation and its spatial distribution. The organism may be exposed to a mixture of the various types of ionizing radiation from radionuclides of different physical and chemical properties. An additional complication, resulting in nonuniformity of dose, is the mobile nature and varied habits of some organisms. Current levels of radioactivity in most areas are too low to detect population and community level effects from ionizing radiation, even in such areas as weapons testing sites. Consequently, the experimental radiation ecologist has been forced to resort to experimental irradiations at relatively high levels by one means or another, or to conduct research in unique areas of high background radiation. Even so, such procedures have inherent difficulties associated with them.

Several areas of relatively high natural radioactivity occur in the world and a limited amount of ecological research has been conducted in such areas (Table 2). Drew and Eisenbud[45] estimated the pulmonary dose from ^{220}Rn received by burrow-dwelling indigenous rodents (*Oryzomys ratticeps* and *Zygodontomys lasiurus*) inhabiting an area of high natural radioactivity in Brazil. However, they did not study the impact of these levels on individuals or populations. On a coastal area of high natural radioactivity in south India, Gruneberg et al.[46] investigated the genetic effects on populations of the black rat *(Rattus rattus)* by comparing skeletal and dental measurements of animals from this area with those of an inland control area. The average gamma radiation level on the coastal area was reported as 7½ times that of the control areas. According to the investigators, the exposure of the rats was some 300 times lower than that at which genetic effects have been observed. They concluded from their observations: "...the work carried out in Kerala... failed to discover positive evidence for genetic effects of low-level radiation in that area... There is no evidence in our data that variance is greater in the irradiated than in the control populations." Considerable ecological research has been conducted in the U.S.S.R. on areas of high natural radioactivity.[47] Studies of human populations occupying areas of high natural radioactivity have also been conducted in Brazil.

Table 2
INVESTIGATIONS OF ANIMAL POPULATIONS OCCUPYING AREAS OF UNUSUALLY HIGH NATURAL RADIOACTIVITY

Locality	External gamma exposure rate	Estimated external doses	Estimated doses from internal emitters
DeKalb County, Ga.	Several times above the average for terrestrial ecosystems	—	—
Upper Colorado River Basin, Utah	16—100 μR/hr	—	—
Kerala Coast, India	180 μR/hr	Rats sustain about 1 rad during their reproductive lifetime	—
Morro do Ferro, Brazil	0.05—3.2 mR/hr	1.3—6.7 rad/year (rodents)	3 rem/year to bone (^{228}Ra); 100 rad/year to tracheobronchial epithelium; 25 rad/year to alveolar epithelium (^{220}Rn et al.)
U.S.S.R.	4—8 mR/hr	35—69 rad/year (voles)	Total body burdens of radium and uranium given, but no dose estimates

From Turner, F. B., *Adv. Radiat. Biol.*, 5, 83, 1975. With permission.

Numerous radioactive areas have been created as a result of nuclear activities such as waste disposal and nuclear testing. Examples of such areas include the Hanford site in the State of Washington and the Columbia River which passes through the site; the Irish Sea in the vicinity of the Windscale Works; the Animas River in the vicinity of Durango, Colo., where uranium milling wastes once entered the river; and White Oak Lake, a waste disposal impoundment of White Oak Creek at the Oak Ridge National Laboratory. Although extensive ecological studies have been conducted in the Columbia River and its estuary and in the Irish Sea, no effects of ionizing radiation on aquatic populations have been observed. This is not surprising as both systems have a high dilution capacity, even when related to the relatively large amounts of radioactivity released into their environments. Observations on the Animas River disclosed that chemicals in milling wastes were limiting or extirpating aquatic biota below the mill.[49] Studies associated with White Oak Lake have revealed some interesting results and these will be discussed later.[50-53] In addition, ecological studies have been conducted at numerous nuclear detonation sites. These include sites of nuclear cratering experiments[54-56] and sites used for testing nuclear weapons.[57,58]

Experimental radiation sources have included X-ray machines which have been used to deliver acute wholebody or gonadal doses to many types of animals including lizards, toads, insects, birds, and small rodents. Medical and dental X-ray units, some of which are portable to facilitate field use, have been used. Encapsulated ^{60}Co and ^{137}Cs radiation sources have also been used in field as well as laboratory studies for external gamma ray exposures. Phosphorus-32, ^{90}Sr, ^{90}Y, ^{131}I, and ^{226}Ra have been commonly used as internal emitters.

Experimental plots have been "seeded" with radionuclides in an attempt to provide a more uniform, realistic exposure of populations to ionizing radiation. For example, ^{137}Cs-labeled sand was distributed within 100-m^2 field enclosures containing free-rang-

Table 3
FIELD EXPERIMENTS UTILIZING LARGE RADIATION SOURCES

General vegetation type	Location	Type of radiation source	Pattern of exposure	Beginning of experiment
Oak-Pine forest	Brookhaven, Long Island, N.Y.	9,500 Ci ^{137}Cs	20 hr/day	November 1961
Old-field	Brookhaven, Long Island, N.Y.	3,100—3,900 Ci ^{60}Co	20 hr/day	1962
Creosote bush desert	Nevada Test Site, Mercury	33,600 Ci ^{137}Cs (shielded)	~ 25 days/month	January 1964
Tabanuco forest	Puerto Rico	10,000 Ci ^{137,134}Cs	Continuous	January 1965
Old-field	Oak Ridge, Tenn.	Fallout simulant (~ 2.4 Ci ^{137}Cs)	Continuous	July 1968
Shortgrass plains	Nunn, Colo.	8,750 Ci ^{137}Cs	Continuous and seasonal	April 1969
Broadleaf sclerophyllous scrub	Cadarache, France	1,200 Ci ^{137}Cs	Continuous	July 1969
Pine, hardwood, old-field	Dawsonville, Ga.	Air-shielded reactor	Variable neutron-gamma flux	March 1959
Northern deciduous forest	Rhinelander, Wis.	10,000 Ci ^{137,134}Cs	20 hr/day	May 1972

Modified from Turner, F. B., *Adv. Radiat. Biol.*, 5, 83, 1975. With permission.

ing cotton rats *(Sigmondon hispidus)* and the effects of this exposure were studied.[59] Small plant communities which occur on granite outcrops in Georgia were transported to simulated outcrops at the University of North Carolina, Raleigh, and exposed to small radioactive particles consisting of feldspar grains coated with ^{90}Y in an attempt to simulate fallout conditions.[60] Such seeding procedures are limited to small areas, specific radionuclides, and small-statnre vegetation. The health and safety aspects of using such procedures must be carefully considered.

Most experimentally controlled studies on effects of chronic irradiation on natural populations and communities have employed large gamma sources (Table 3). Prior to establishment of these rather extensive studies between 1959 and 1972, Breslavets suspended a ^{60}Co source in a field in the U.S.S.R.[61] As an alternative to placing a source in the field, transplanted natural assemblages of plants were irradiated in a gamma radiation facility established at Emory University, Atlanta, Ga.[62]

Some obvious limitations exist in studies involving large point radiation sources with the foremost being the very high levels of radiation required to produce observable effects, many orders of magnitude above current environmental levels, and the restriction to terrestrial environs. In addition, the radiation field from a point source diminishes rapidly with distance. This constrains the location and size of study plots at higher levels near the source. Further, large fixed source studies are more suitable for stationary plants than mobile animals. Turner[18] discusses these limitations and contrasts these artificial radiation fields with those associated with fallout from nuclear weapons testing. At the Nevada Test Site, Mercury, Turner, French and associates conducted studies in a radiation field designed for relatively low level long-term chronic irradiation of animals.[18,63] These studies are rather unique in the discipline of radiation ecology and have served to illuminate the role of irradiation on the population dynamics of animals in their natural habitat. Contributions to knowledge on the effects of chronic irradiation on vegetation emanate from other studies listed in Table 3. However, these studies contributed only in a limited way to the understanding of irradiated animal populations. The advantage of the work on animals at the Nevada Test Site was that

Table 4
FIELD STUDIES OF ANIMALS AT SITES OF ANTHROPOGENIC SOURCES OF ENVIRONMENTAL RADIATION OTHER THAN EXPERIMENTAL RADIATION SOURCES LISTED IN TABLE 3

Locality	Sources of radiation	Nature of exposure	Estimated doses or dose rates	Animals studied
Oak Ridge, Tenn.	Radioactive wastes, dry bed of White Oak Lake	Continuous	Variable (15—30 rad/month)	Rodents *Sigmodon hispidus et al.)*
	Radioactive wastes, sediments of White Oak Lake	Continuous	10.9 rad/day	Minnows *(Gambusia affinis, Chironomous tentans)*
	Radioactive waste in sediments and water, internal emitters	Continuous	235 rad/year	Snails *(Physa heterostropha)*
Nevada Test Site, Mercury	Plutonium	Continuous	Unknown	Kangaroo rats *(Dipodomys ordii)*
	Tritium, other internal emitters	Continuous	2 rad/month	Kangaroo rats
Animas River, Colo.	Uranium mill wastes	Continuous	Not computed	Benthos, fish

Modified from Turner, F. B., *Adv. Radiat. Biol.*, 5, 83, 1975. With permission.

the source was designed to provide a reasonably uniform field and a barrier fence was employed to prevent emigration and immigration of lizards and small rodents at the site. Adequate studies of animal populations in irradiated sites of limited area require large populations in order to observe effects with statistical reliability. Thus, populations of birds or large vertebrates would not be expected to be adequate, while those of invertebrates and small mammals may be suitable for study around a central radiation source. Table 4 lists field studies of animals in the vicinity of anthropogenic environmental radiation other than the experimental sources listed in Table 3.

B. Dosimetry

The difficulty in estimating dose received by organisms in field studies is dependent on habitat, mobility, size and shape of the organism, type of radiation — its energies and source, and whether external, internal, or a mixture of emitters is involved. Measurement of dose from wholebody X- or gamma irradiation of a single organism in the laboratory would be relatively simple, while determination of dose received by organisms in a fallout field of many radionuclides would be difficult. Unfortunately, some investigators neglect to present adequate detail on dose determination and the variability associated with their estimate. Consequently, there is sometimes doubt as to the actual levels of radiation from which specific effects were observed. This is particularly true when external and internal emitters are involved either singularly or in a mixture; for example, the dose received by an aquatic organism or fish eggs in an aqueous medium containing radionuclides. In an excellent literature summary on methods of investigating effects of ionizing radiation on fish eggs, Polikarpov[64] stated: "From the very beginning of radiobiological research on fish eggs, the weakest point has been — and probably still is to a large extent — the dosimetry."

In a genetic study of fruit fly *(Drosophila)* populations at the Pacific Proving Ground, investigators were dependent on general exposure levels furnished to them by

Table 5
RADIATION DOSAGE (mrad/year) RECEIVED BY TWO TYPES OF MARINE ORGANISMS FROM NATURAL SOURCES

Type of organism and its location in the sea	Type of radiation: Cosmic	Sea	Internal	Approx. total dose
Large fishes				
Near sea surface	35	0—9	28	64
At 100 m depth	0—5	0—9	28	30
Microorganisms (Mean radius 0.01 mm or less):				
Near sea surface	35	3—6	[a]	39
At 100 m depth	0—5	3—6	[a]	5
Buried in deep sea sediment	[a]	40—620[b]	[a]	40—620

[a] Insignificant dose.
[b] Dose from radium in clay.

From Chipman, W. A., *Marine Ecology*, Vol. 1 (Part 3), Kinne, O., Ed., Copyright 1972, John Wiley & Sons, New York, 1579. Reprinted by permission of John Wiley & Sons, Ltd.

the U.S. Atomic Energy Commission (USAEC).[57] Similar exposure uncertainties existed in the early 1950s at the Nevada Test Site for the study of populations around ground zeros following nuclear detonations. In later years, investigators at the site had an opportunity to estimate doses received by surviving biota with dosimeters placed in the vegetation or implanted in rodents and lizards. This opportunity came about through development of solid state dosimeters and the invitation of ecologists to participate in predetonation planning.

Woodhead,[65] who was interested in the exposure of aquatic organisms of the Irish Sea in the vicinity of Windscale Works, England and also in the broader question of dose commitment to marine organisms in general, presented an interesting paper at an International Atomic Energy Symposium, *Radioactive Contamination of the Marine Environment*. He considered the major source of ionizing radiation in the marine environment as due to fallout from weapons testing and contrasted it with background levels. The incorporation of alpha emitters (principally ^{210}Po) was considered the main source of natural background dose with most of the remainder attributed to ^{40}K. He commented that the assumption of uniform internal dose would lead to underestimation of dose rate to a particular tissue by ^{210}Po and that, in seawater, only ^{40}K makes a significant contribution to background. Further, cosmic radiation is a more important contributor to dose rate at the surface of the sea than at the bottom, where the underlying sediments are a significant source of radiation to benthic organisms. Table 5 illustrates some of these relationships. The penetrating ability of various types of radiation in the aquatic environment is an important consideration. For example, alpha particles in seawater would not penetrate the surface of a fish while an alpha emitter incorporated into tissue could contribute significantly to the overall tissue dose.

Thermoluminescent dosimeters (TLD), described in Volume I, Chapter 3, are very useful for measurement of total dose and they have been used widely in ecological studies. In a further extension of his efforts to estimate dose commitment to marine organisms, Woodhead[66] implanted TLDs in Irish Sea plaice with the resulting observation that measured dose was three orders of magnitude larger than that calculated in earlier research.

In a study of the mosquito fish *(Gambusia affinis)* in White Oak Lake, Blaylock[53] calculated the dose rate contributions from water and internal emitters and that from *in situ* gamma radiation in sediments, concluding the former were insignificant contributors to dose rate. In a later investigation involving *in situ* dose measurements,[67] it was concluded that the sediment could not be considered an infinite plane of negligible thickness, as the highest concentrations of radionuclides were at sediment depths greater than 15 cm. Utilizing TLDs, Trabalka and Allen[68] revised the dose estimate.

Following the draining of White Oak Lake, Dunaway and Kaye[51] studied mammal populations on the lake bed. The dose rate was estimated by placing glass rod dosimeters at various distances above the lake bed and subcutaneously within cotton rats. (Figure 1).

Implanting of dosimeters to estimate dose received by animals has now become rather commonplace. Turner and Gist[56] implanted dosimeters in lizards prior to the cratering experiment, SEDAN, conducted at the Nevada Test Site; French[70] used them in a study of a laboratory population of wild deer mice *(Peromyscus maniculatus)* exposed to relatively low-levels of radiation; and Watson and Templeton[71] incorporated their use in a study of dosage received by the large-scale sucker *(Catostomus macrocheilus)* in the Columbia River near the Hanford plant.

Ecological studies involving placement of large radiation sources in terrestrial ecosystems have been concerned with radiation dose as a function of distance from the source (horizontally and vertically), its variability at common distances, and factor accounting for such variations. Doses received by both plants and animals have been estimated.

IV. ACUTE IRRADIATION INVESTIGATIONS

A great number of experiments have been conducted on response of organisms to acute radiation stress. Such studies have involved many species, differing experimental conditions, and varied end points of damage have been quantified. Overall quality and statistical validity of these experiments appears extremely variable. For these reasons, the authors have not attempted to prepare a well-integrated, comparative summary. Instead, they have briefly cited findings from a wide assortment of literature under headings organized by convenient taxonomic groupings. These findings form a basis upon which some general statements can be formulated. Such general conclusions are found at the end of this section, as well as in the final chapter.

In the early period of investigation with wild organisms, many researchers were concerned with determining the dose at which 50% of the organisms in an experiment would perish within a specific time period, e.g., 30 days ($LD_{50(30)}$). This dose, sometimes called the "median lethal dose," was used as a general measure of radiosensitivity. Published results rarely included confidence limits and were applicable mainly to laboratory situations. Later, attempts were made to overcome these limitations by conducting field work and examining the LD_{50} concept in more detail. In a report of an investigation on the radiation sensitivity of several marine species, White and Angelovic[72] stressed the need to develop functional response curves relating LD_{50}s to the time for which the LD_{50} was computed. They termed such a function a "mean lethal-dose time curve" and concluded that such curves described radiation tolerances better than a single, commonly used $LD_{50(30)}$. Lists of median lethal doses have limited value as it is often difficult to compare results;[21] therefore, the authors will not attempt to prepare exhaustive lists, but will utilize limited lists to illustrate a point in their discussion. It is not implied that the computation of median lethal doses has little value. On the contrary, they are useful in planning experiments and comparing radiation sensitivity of broad groups of organisms or the same species exposed to additional stresses. However, care must be used in interpreting values appearing in the literature.

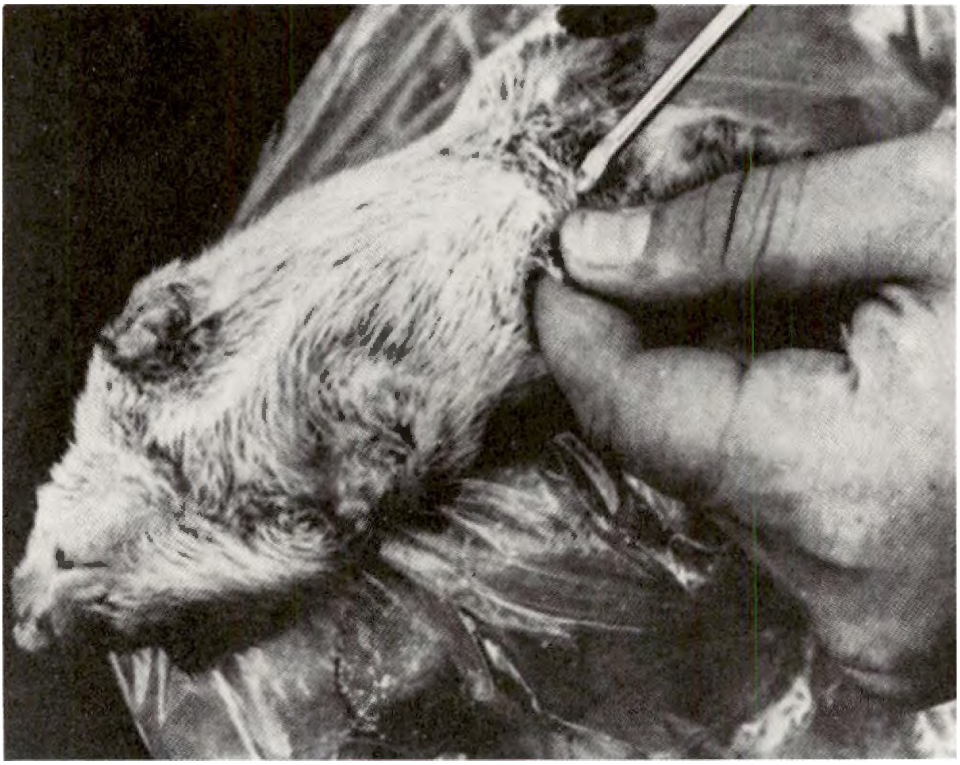

FIGURE 1. Subcutaneous insertion of glass rod dosimeter in a cotton rat *(Sigmodon hispidus)* in the field. (From Kaye, S. V., Use of minature glass rod dosimeters in radiation ecology, *Ecology*, 46(1/2), 201, 1965. Copyright 1965 by the Ecological Society of America.)

A. Invertebrates

Perhaps the most widely studied group of organisms in regard to effects of ionizing radiation is the insect. Undoubtedly this is due to their suitability for genetic studies and, in addition, to interest in the development of the sterile-male technique for controlling insect populations. One needs only to peruse the bibliographies of Bingelli listed in Appendix A and know that her efforts were discontinued due to the enormity of the task in recent years. O'Brien and Wolfe[12] attempted the tremendous task of reviewing some of the literature. They state:*

> "It is widely known that insects are insensitive to radiation when compared to vertebrates. ...adult insects are at least 100 times less sensitive to the lethal effects of radiation than are vertebrates, and this phenomenon must be explained. The most generally accepted explanation is based on two facts: (1) a generalization which was formulated in 1906 as the Bergonie-Tribondeau "law" — the sensitivity of cells to irradiation is in direct proportion to their reproductive activity and inversely proportional to their degree of differentiation; (2) a special feature of insects — after they hatch from the egg, very little cell division occurs during larval life. Cell division and differentiation of tissues occur instead during embryonic development in the egg, so that, in larval life, growth occurs primarily by enlargement of cell volume without an increase in cell number. There are other short bursts of mitotic activity; just before molting and (where a pupal form occurs) in the later stages of pupation.
>
> It follows that dividing insect cells are as sensitive as dividing vertebrate cells, but the peculiarly static quality of the adult insect's cell life makes it insensitive to radiation. However, certain cells do divide in the adult — the cells of the gonads — and one finds that these dividing cells are in fact very sensitive to radiation, so that quite low doses can sterilize the insect or cause the production of genetically deranged gametes."

* From O'Brien, R. D. and Wolfe, L. S., *Radiation, Radioactivity, and Insects*, O'Brien, R. D. and Wolfe, L. S., Eds., Academic Pr[illegible] ork [illegible] ni sion.

It has been observed that juvenile forms of insects are more sensitive than adults as a consequence of the greater number of dividing cells of juvenile forms. Further, males are more sensitive than females; a single dose is more effective than a fractionated dose; and survival is a function of age, with older insects dying before young insects at a given dose. The latter is attributed to acceleration of normal aging processes. Observations by Willard[73] on effects of ionizing radiation on populations of the plum curculio *(Conotrachelus nenuphar)* resulted in some possible exceptions to these general statements. Acute X-irradiation at levels from 0 to 9 kR resulted in an increase in mean-life expectancy (which was not statistically significant) up to a certain dose and then a decrease for both males and females, with the death rate being higher for males than females. The net reproductive rate showed a similar functional change. In a study of the relationship of the number of untransformed larvae of *Trogoderma sternale* to the method of dose delivery, Howden and Auerbach[74] observed the expected result of a fractionated dose being less effective than a single dose.

Comparative radiosensitivity of 37 species from 8 orders was investigated by Willard and Cherry[75] with the conclusion that large, long-lived adults were more sensitive than small, short-lived adults and that a poor correlation existed between phylogeny and radiosensitivity. Studies of competition between two species of *Drosophila* by Blaylock[76] disclosed that dominance depended on the dose level and that irradiated flies placed in competition with nonirradiated flies resulted in a decrease in frequency of the former. In a study involving two species of adult flour beetles *(Tribolium confusum* and *T. castaneum)*, Erdman[77] considered the effects of temperature and X-irradiation on reproductive abilities. Productivity increased with temperature within the range of the experiment and decreased with increasing levels of radiation. The proportions of the two species in coexistence varied with temperature and radiation, with *T. castaneum* consistently higher than *T. confusum*, the latter exhibiting reduced productivity. A very important comment was made by Erdman: "Responses to radiation of single-species populations cannot be used to predict those of mixed-species populations."

Exposure of mixed populations of soil invertebrates to high levels of radiation (10 to 200 krad) disclosed variable sensitivity between and within taxonomic groups.[78] Possibly due to predator-prey interactions some species increased at the lower levels of irradiation. As with many other investigations, there was evidence for differential radiosensitivity between invertebrates in culture and those in soil.

Rather extensive investigations have been conducted on brine shrimp *(Artemia salina)*.[11] Engel and Davis[79] demonstrated that the $LD_{50(25)}$ was considerably larger for adults than for nauplii. Also, salinity and radiation reduced survival of females more than males. Population density of the organism was also an important consideration in evaluating the response of population growth to irradiation. A dose of 500 rad increased growth at all densities with the greatest increase being at 8 mℓ/nauplius. In another study of the effects of radiation on populations of brine shrimp,[80] it was observed that at the end of a 20-week investigation the population size at all doses was the same, even though reproductive potential was diminished at higher doses. To quote the authors:*

> "It was demonstrated that the population cultures may be maintained with only a small part of the reproductive potential exhibited in the pair matings. Therefore, we find that the results of pair matings must necessarily be used to assess the amount that the reproductive potential of *Artemia* is decreased due to various doses of irradiation."

* From Holton, R. L., Osterberg, C. L., and Forster, W. O., Effect of gamma irradiation on the maintenance of population size in the brine shrimp *Artemia*, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1198.

Table 6
AMOUNTS OF RADIATION REQUIRED TO KILL 50% OF THE RAINBOW TROUT, *SALMO GAIRDNERI*, IRRADIATED AT VARIOUS STAGES IN THEIR LIFE CYCLE

Stage in life cycle	LD_{50} (R)
	At end of yolk stage
1 cell	58
32 cell	313
Germ ring	454—461
Eye	415—904

Adapted from Welander, A. D., *Growth*, 19(4), 227, 1954. With permission.

The effects of radiation in combination with other experimental variables have been considered in several studies with invertebrates. For example, Angelovic and Engel[81] found that respiration of brine shrimp nauplii was affected by salinity and radiation, and by the interaction of both factors. The interaction of radiation, salinity, and temperature on ionic regulation in the blue crab *(Callinectes sapidus)* was also studied.[82] Immature crabs were acutely irradiated at a dose of 10 krad and maintained at three temperatures and two salinities. The authors observed an interaction of radiation with temperature and salinity and concluded: "...the degree of radiation damage to ionic regulation in the blue crab was influenced by the crabs' environment before and after irradiation."

B. Vertebrates

Studies on effects of acute irradiation of wild vertebrates have been restricted to small forms rather than to the larger ones, such as marine mammals and ungulates. Undoubtedly this is in part due to the ease and lower cost of manipulation, as well as to the relative abundance of the smaller forms. Vertebrate studies have concentrated on fish, amphibians and reptiles, birds, and small mammals, particularly the latter.

1. Fish

Much concern has been expressed as to the effects of the introduction of waste nuclear products into rivers, lakes, seas, and oceans. Of particular concern are the commercial and sport fisheries. Acute irradiation studies are rather limited as more interest has been focused on chronic irradiation of fish eggs. Polikarpov[27] listed studies on irradiation of eggs of marine, brackish, and freshwater fishes of various taxonomic groups.

A study by Welander[83] on the effects of ionizing radiation on various life stages of rainbow trout *(Salmo gairdneri)* illustrates the relative sensitivity of early stages (Table 6). In an earlier study, the effects of irradiating the parent of this species on the embryos and young as well as on spawning activity of the parent were examined.[84] X-ray exposures ranging from 50 to 2500 R were given to adult trout. It was observed that

ionizing radiation did not hasten or delay spawning. At the highest level, some of the fish died before spawning. According to the authors:*

> "The mean mortalities of the eggs obtained from parents subjected to 500 or more r units were significantly greater than that of the eggs from the control parents. Most of the eggs which died during the incubation period contained conspicuously abnormal embryos. ...However, as the amount of radiation increased the relative abundance of malformed embryos increased and the degree of development attained decreased."

Mortality of fry of irradiated parents was significantly higher than the control for all levels of radiation.

Angelovic et al.[85] observed interactions of temperature, salinity, and ionizing radiation on the $LD_{50(30)}$ of an estuarine fish, *Fundulus heteroclitus.* The fish tolerated more radiation at the upper end of its temperature range at low salinity, with a reversal observed at the low temperature range. It was observed that lethal effects of ionizing radiation may result from damage to osmoregulatory mechanisms, as ^{22}Na was lost more rapidly by irradiated fish than controls. In another study of interaction of radiation and temperature, Edmundson[86] observed no effects of the combined action of these two factors on growth of juvenile rainbow trout within the 4 weeks following doses of less than 1 krad.

Various effects other than mortality have also been studied in fish. For example, Ulrikson[87] exposed blue gills *(Lepomis macrochirus)* to 1, 2, and 3 kR of radiation, following which blood samples were taken at various time intervals. Within 2 to 24 hr after irradiation, a decrease of approximately 50% was observed in beta globulins, alpha globulins, and albumins, followed by hemocentration. Holzberg and Schroder[88] observed a reduction of male aggressiveness in the convict cichlid fish *(Cichlasoma nigrofasciatum)* following a fractionated dose of 1 kR of X-rays (500 R, 24 hr apart) to oogonia and spermatogonia.

2. Amphibians and Reptiles

Limited observations have been made on the effects of ionizing radiation on amphibians and reptiles. Some investigators have attempted to relate radiosensitivity to chromosome attributes in this group of organisms. For example, Sparrow and others[89] investigated the relationship of radiosensitivity to nuclear and chromosome volumes. They observed that following a dose of 1 kR, median survival time increased with increasing chromosome and/or nuclear volume. Conger and Clinton[90] also studied nuclear characteristics in amphibians as related to radiosensitivity. They related interphase chromosome volume (ICV) to radiosensitivity and concluded that at the same ICV, herbaceous plants were about seven times less radiosensitive than amphibians, while woody plants were three times less sensitive.

Several investigations have focused on survival and natality of irradiated individuals. For instance, Landreth et al.[91] wholebody irradiated various life stages of the toad, *Bufo woodhousei,* and found that survival varied between adults, juveniles, and tadpoles. Cosgrove[14] reported the median lethal exposure for several species of reptiles: $LD_{50(90)}$ 300 to 400 R for snakes; $LD_{50(120)}$ 1030 R for a turtle. The hematopoietic syndrome seemed to dominate at LD_{50} exposures. During a 2-year period in western Texas, Tinkle[92] investigated the effects of acute X-irradiation on natality, density, and breeding structure of free-ranging lizards, *Uta stansburiana.* The investigation included two 2-acre study areas; one a control and the other containing lizards that received gonadal doses of 450 R prior to the breeding season. After 2 years of investigation, the plot treatments were reversed. A 50% decline in natality was observed in

* From Foster, R. F., Donaldson, L. R., Welander, A. D., Bonham, K., and Seymour, A. H., *Growth,* 13(2), 119, 1949. With permission.

the irradiated individuals, which in turn resulted in a decrease in density a year following irradiation. Apparently, the results were duplicated in the switchback experiment.

3. Birds

Mellinger and Schultz[15] summarized literature on the effects of ionizing radiation on wild birds. The following notes were obtained from the papers they reviewed: contrasting the radioresistance of the eastern bluebird *(Sialia sialis)* with the laboratory chicks and ducklings of the same age, Norris[93] found that week-old bluebirds might have greater radioresistance. Effects on breeding plumage of the weaver finch *(Quelea quelea)* were investigated following wholebody X-ray exposures of 50 R to 1 kR.[94] No effects were noted at doses other than at 1 kR, where regenerated feathers of the facial mask were unpigmented. Lofts and Rotblat[95] subjected male weaver finches to whole body radiation and observed abnormal histological changes to the testes at 420 to 1060 R. No testicular damage was found at 50 and 210 R. Willard[96] observed progressive stunting of growth and feather elongation when nestling eastern bluebirds were given from 300 R to 2 kR total exposure (43 R/min) at 2 and 16 days of age. Feather growth decreased an average of 10% in 2-day old nestlings exposed to 300 to 500 R. A 50% reduction in growth occurred when nestlings were exposed to approximately 1.5 to 2 kR. Less of an effect on growth was observed when 9-day old birds were given similar dosages, but marked feather inhibition continued. Willard also observed that birds of the 2-day old group receiving 800 to 900 R were usually able to leave the nest box at the normal time; however, their weakened condition and "subnormal flying ability" rendered them more vulnerable to predation during this critical fledgling period.

Garg et al.[97] exposed starlings *(Sturnus vulgaris vulgaris)* to gamma radiation of from 300 to 3000 rad. Extensive necrotic changes occured in the bone marrow, spleen, and duodenum. Death at exposure of 1000 rad or more was assumed to be from irreparable vital tissue damage. Tester et al.[98] studied the median lethal dose of three species of ducks, namely, the blue-winged teal *(Anas discors)*, green-winged teal *(A. crecca carolinensis)*, and shoveler *(Spatula clypeata)*. The $LD_{50(30)}$ was 715, 485, and 894 R, respectively, as determined by exposure to gamma radiation from ^{137}Cs. Workers were unable to observe courtship behavior modification in waterfowl following a high sublethal dose of radiation.[99] Single exposures ranging from 500 to 2025 R and cumulative exposures from 500 to 5316 R to the ovaries of ring-necked pheasants *(Phasianus colchicus)* had no observable effect on ovarian tissue structures, egg production, or plumage coloration.[100] At acute exposures of 2025 R, average survival of pheasants was less than 5 days with death "probably due to a breakdown of the hemopoitic balance." Stearner and co-workers[101] observed a definite dose rate effect on mortality of exposed parakeets by plotting mortality vs. dose for varied exposure times (Figure 2).

4. Small Mammals

Sacher and Staffeldt[102] tabulated some $LD_{50(30)}$ values for small rodents (Table 7). A large number of these values were obtained by Dunaway and co-workers[105] who exposed animals to gamma radiation from a ^{60}Co source. At high doses they observed rapid weight loss in all species with considerable interspecific differences in weight loss at low levels. They observed various symptoms of radiation damage: "conjunctivitis, ataxia, diarrhea, passiveness, cessation of feeding, aggressiveness, and pelage graying". These feral animals were maintained in captivity and the influence of such captivity on the observed response is not clear.

Reproduction was observed in another laboratory-confined animal by DiGregorio et al.,[106] who acutely gamma-irradiated white-footed mice *(Peromyscus leucopus)* at near the $LD_{50(30)}$ level. Animals exposed to 950 rad were mated with either irradiated

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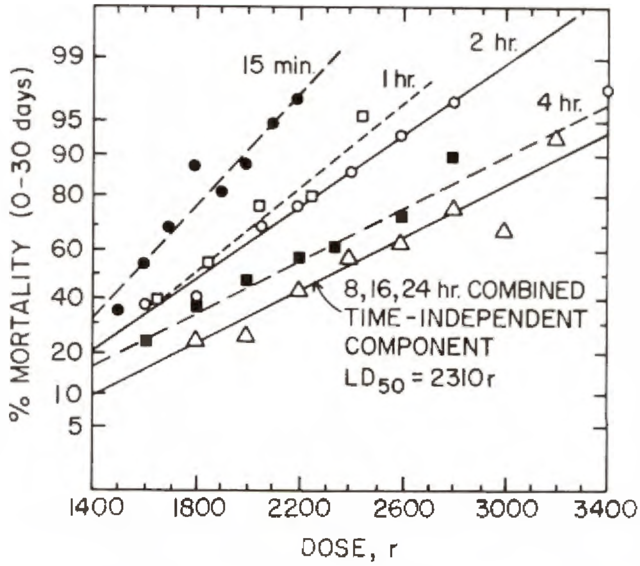

FIGURE 2. Effect of exposure time on dose-mortality relations of acute irradiations of the parakeet. (From Stearner, S. P. et al., Acute radiation mortality in the parakeet, in Biological and Medical Research Division, Summary Report January through December 1960, U.S. AEC Rep. ANL-6368, Argonne National Laboratory, Illinois, 1961, 5.)

or nonirradiated mice. When both parents were irradiated, young were not produced within 3 months, but when an irradiated animal was mated with a nonirradiated animal, they produced young. Thus, at this level of irradiation, populations will be reduced by direct lethality and by diminished natality. Reproduction by irradiated female cotton rats trapped in the wild and released to field enclosures with unirradiated males was studied by Pelton and Provost.[107] Pregnancies were reduced by wholebody exposures between 500 and 1050 R and prevented by an exposure of 1200 R. Mean litter sizes were also reduced in the 500 to 1050 R exposure range.

Some years preceding the studies mentioned above, Blair[108] exposed gonads of male deer mice *(Peromyscus maniculatus)* to 500 R of X-rays and released them into nest boxes placed in the field. This was an attempt to apply gonadal doses of sufficient magnitude to introduce mutations into a natural population. Observed reductions in litter size were attributed to such induced mutations. However, population size was maintained through 4 years of irradiation of sexually mature male mice, which implied that the populations were controlled by density-dependent factors, not radiation. In a later paper, Blair[109] reviewed this and similar research on *Peromyscus leucopus* and the toad, *Bufo valliceps*. He summarized:*

"The results with all three of these species indicate that their natural populations are capable of surviving much genetic damage without impairment of their success in their natural environments. All of these species share a high attrition on the large numbers of young produced each generation, and this provides an agency for intensive selection. It is to be further expected that, under this regime, recessive mutants will be eliminated as they are exposed through inbreeding in future generations."

Two species of wild rodents exposed to acute gamma radiation were studied under field conditions by Golley and Gentry.[110] Four weeks after release of individuals in

* From Blair, W. F., Effects of radiation of natural populations of vertebrates, in *Recent Advances in Botany*, Vol. 2, University of Toronto Press, Canada, 1961, 1377. Copyright, Canada, 1961 by University of Toronto Press.

Table 7
$LD_{50(30)}$ VALUES FOR RODENTS ACUTELY EXPOSED TO GAMMA RAYS

Species	Sex	Measured $LD_{50(30)}$ values (R)
Ochotona princeps	M,F	380—560
Citellus richardsoni	M,F	1260
Mus musculus	M	829—851
	F	799—802
Rattus natalensis	M,F	823—1044
R. norvegicus lab.	M	949—1330
	F	795—1057
Peromyscus leucopus	M	1091
	F	1043
P. gossypinus	M,F	1130
P. maniculatus	M,F	919
P. polionotus	M,F	1125—1147
Sigmodon hispidus	M	966—1155
	F	950
Reithrodontomys humulis	M	986
	F	908
Oryzomys palustris	M	584
	F	480
Tamias striatus	M,F	950

Modified from Sacher, G. A. and Staffeldt, E., Species differences in sensitivity of myomorph and sciuromorph rodents to life shortening by chronic gamma irradiation, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1042; also with additions from References 103 and 104.

two-acre field enclosures, old-field mice *(Peromyscus polionotus)* and house mice *(Mus musculus)* were trapped and taken to the laboratory. One half of the individuals were irradiated (wholebody) at the $LD_{50(30)}$ and the other half treated as controls. Both groups were returned to the field enclosures and retrapping was resumed at weekly intervals for a period of 4 weeks in order to evaluate survival. Survival in the field was the same as in the laboratory for the house mouse, but significantly lower in the field for the other species. Further, weight gain and distance between captures was significantly reduced in the *Peromyscus* survivors, which suggested a "substantial incidence of radiation sickness."

O'Farrell and colleagues[111] studied the effects of ionizing radiation on survival, longevity, and reproduction of free-ranging pocket mice *(Perognathus parvus)* trapped in the wild, irradiated at various levels with a ^{60}Co source, and returned to the site of capture. Utilizing recapture data, they computed the $LD_{50(30)}$ for these free-ranging animals and contrasted it with the $LD_{50(30)}$ for animals maintained in the laboratory. No significant difference was observed between the two values. Further, they observed no induced sterility in free-ranging males, but all irradiated females appeared to be sterile in subsequent breeding seasons. In a somewhat similar study involving the meadow vole *(Microtus pennsylvanicus)*, Iverson and Turner[112] studied seasonal differences (May and November) in the combined effects of natural mortality and that due to radiation. The $LD_{50(30)}$ for animals irradiated in May, released into the field and retrapped approximately 30 days later was not significantly different from animals irradiated and confined in the laboratory. However, a similar comparison for animals

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irradiated in November disclosed a significantly lower $LD_{50(30)}$ value for the field animals. According to the authors:*

"These results support the suggestion that extrapolation from the laboratory results may overestimate the radioresistance of free-ranging small mammals. The results were interpreted to indicate that the decrease in radioresistance was an indication of (and was caused by) the general level of stress on the population. The hypothesis that decreased radioresistance was associated with breeding was not supported."

In a study of social interaction of pikas *(Ochotona princeps)* in field enclosures as influenced by 500 R acute irradiation from a ^{60}Co source, Markham and Whicker[113] observed higher survival rates and longer survival times of pikas confined in individual cages as contrasted with those in field enclosures which were free to interact. These findings substantiated those from a previous study, in which it was observed that pikas in the natural environment exhibited a lower $LD_{50(30)}$ than animals maintained in cages after irradiation.[103]

Tryon and Snyder[114] exposed the eastern chipmunk *(Tamias striatus)* to 200 and 400 R of gamma rays and released the animals into the field at the site of initial capture. Curiously, survivorship curves for irradiated animals were significantly higher than for the controls. This was attributed to increased survival of individuals irradiated early in life and to a more rapid disappearance of nonirradiated individuals from their territories. Animals missing from their territories or adjacent area were considered dead, even though they may have simply emigrated. In a continuation of this study, Snyder et al.,[115] investigated range parameters. A comparison of irradiated and nonirradiated individuals in the same study area disclosed a significant difference in range and movement between populations of the two groups, but only for those populations with the largest ranges. "Thus, it was speculated that reduction in range size as a result of radiation exposure may occur only when that range size exceeds some threshold level." The investigators compared the response of males and females and at one study site found a consistent reduction, as compared to controls, in home range and length and successive recapture distances of irradiated males. In another study area, however, there was no difference in range parameters between irradiated and control animals.

A few studies have looked at blood changes following irradiation of wild rodents. For example, Haley et al.[116] noted reductions in spleen weight, platelet, and leucocyte numbers in kangaroo rats *(Dipodomys merriami)* that received exposures in the range of 25 to 400 R. Kitchings et al.,[117] studied blood changes in rice rats *(Oryzomys palustris)* and cotton rats exposed to doses of 200 and 600 rad. No difference in the response between wild-caught and laboratory-born individuals of the two species was observed. The most striking difference between the two species was in the red cell response.

Little work has been done in the area of effects of irradiation on the metabolism of radionuclides. However, a study of excretion rates of ^{60}Co and ^{54}Mn from pine voles *(Microtus pinetorum)* following irradiation in field and laboratory animals disclosed no significant difference between the two groups of animals.[118] However, the two radionuclides were excreted more rapidly in the field than in the laboratory.

Hibernation patterns of ground squirrels *(Citellus tridecemlineatus)* following wholebody irradiation of 1250 rad from a ^{60}Co source were observed by Barr and Musacchia.[119] Individuals irradiated while torpid as contrasted to those irradiated while active exhibited greater survival. Survival was also increased as a result of post-irradiation hibernation. Survival was apparently not affected by the post-irradiation ambient temperature.

* From Iverson, S. L. and Turner, B. N., *Radioecology and Energy Resources*, Cushing, C. E., Jr., et al., Eds., Dowden, Hutchinson & Ross, Stroudsburg, Pa., 1976, 359. With permission.

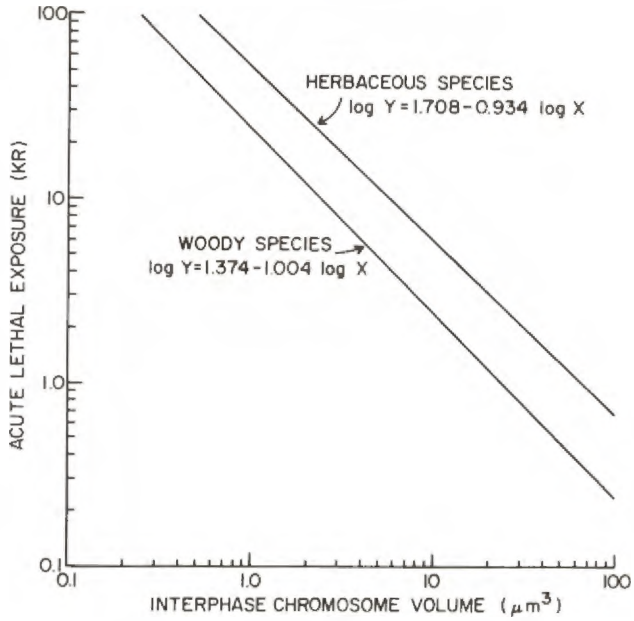

FIGURE 3. Relation between interphase chromosome volume (ICV) and acute lethal exposure for woody and herbaceous spermatophytes. (After Sparrow, R. C. and Sparrow, A. H., *Science*, 147, 1449—1451, 19 March 1965. Copyright 1965 by the American Association for the Advancement of Science.)

Table 8
THE PRINCIPAL NUCLEAR AND ALLIED FACTORS INFLUENCING PLANT RADIOSENSITIVITY[120]

Factors tending toward high sensitivity	Factors tending toward high resistance
Large nucleus (high DNA)	Small nucleus (low DNA)
Large nuclear/nucleolar volume ratio	Small nuclear/nucleolar volume ratio
Much heterochromatin	Little heterochromatin
Long chromosome arms (large chromosomes)	Short chromosome arms (small chromosomes)
Acrocentric chromosomes	Metacentric chromosomes
Normal centromere	Polycentric or diffuse centromere
Uninucleate cells	Multinucleate cells
Low chromsome number	High chromosome number
Diploid or haploid	High polyploid
Sexual reproduction	Asexual reproduction
Slow rate of cell division (long intermitotic time)[a]	Fast rate of cell division (short intermitotic time)[a]
Long dormant period[a]	Short or no dormant period[a]
Meiotic stages present at dormancy[a]	Meiotic stages not present during dormancy[a]
Slow meiosis and premeiosis[a]	Fast meiosis and premeiosis[a]
Low concentration of protective chemical constituents, e.g., ascorbic acid	High concentration of protective chemical constituents

[a] Factor of particular importance only under conditions of chronic irradiation.

C. Plants

A tremendous volume of literature exists on the effects of acute irradiation on plants. However, the work which probably contributed most to basic theory and pre-

dictability in the area of plant radiobiology was conducted by Sparrow and colleagues at Brookhaven National Laboratory. The major contribution of this work was to demonstrate, using a large number of species of higher plants, the quantitative dependence of species radiosensitivity on characteristics of the cell nucleus.[120] In particular, it was demonstrated that radiosensitivity of a wide variety of species could be predicted quite accurately if the average ICV was known. Predictable relationships followed from the early observation that plants with large chromosomes tend to be comparatively sensitive to radiation, while those with small chromosomes are more resistant. The mathematical relationship depends on the way that sensitivity is measured and upon certain plant groupings. Figure 3 illustrates the relationship between acute lethal exposure and ICV for woody and herbaceous species.

Figure 3 illustrates some interesting features. For example, woody species tend to be about twice as sensitive as herbaceous species, for a given ICV. Also, higher plants exhibit a large range of sensitivity, with acute lethal exposures ranging from less than 1000 to nearly 100,000 R. Lesser effects, such as severe growth inhibition, may result from exposures of only a few hundred roentgens in the most sensitive species.[121] The most sensitive plant species include coniferous trees, which dominate several major ecosystems of the world. This group of plants exhibits radiosensitivities in the same range as the mammals.

Systematic studies on the relation of a large number of cellular and nuclear features of plants to radiosensitivity have revealed several interesting tendencies (Table 8). Sparrow provides a full discussion of these cellular and subcellular factors.[120] One of the major determinants of radiosensitivity besides ICV is ploidy. Polyploids, organisms which have redundant sets of chromosomes, tend to exhibit more resistance to radiation. Interestingly, polyploids also seem to be more resistant to other forms of stress and perhaps selectively evolved in harsh environments. Lower plant forms, such as mosses, lichens, and unicellular species are generally highly resistant to radiation. The explanation for this can generally be found at the cellular level, as most lower plants feature small chromosomes, diffuse centromeres, and asexual reproduction.

Gunckel and Sparrow[122] prepared an extensive tabulation of radiation effects in plants. For each study they indicated the species involved, nature and location of effects, type of radiation, dose rate and duration of exposure. In this paper, biochemical, physiological, and morphological aspects of radiation damage are also reviewed. This includes discussion of radiation effects on pigmentation, photosynthesis, flowering, and morphogenetic change.

The student of plant radiobiology should also investigate the literature on radioresponse of plants exposed as seeds. A good review was prepared by Osborne and Constantin.[123] As is the case with actively growing plants, the radiosensitivity of seeds is predictable on the basis of nuclear and chromosome volume.[124]

D. General Comments

One of the major points that emerges from examination of the literature on biological effects of acute irradiation is the tremendous range of sensitivity between species. Large variations also exist within many species, depending on a plethora of factors. Figure 4 suggests possible ranges of sensitivities to the lethal effects of acute radiation for a variety of taxonomic groups. The lower ends of the acute dose ranges include the most sensitive species and life stages, while the upper ends are generally adult forms of the most resistant species.

It is important to note that virtually all organisms require an acute dose well in excess of 100 rad before significant prompt mortality can be expected. In fact, significant disruption of most ecological communities is likely to require 1000 rad or more. These are very high doses, the kind that could only be found in areas of limited size

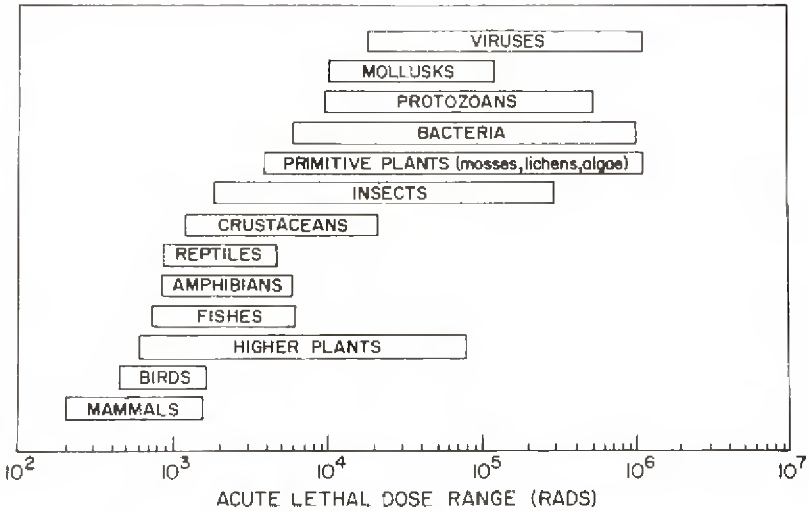

FIGURE 4. Approximate acute lethal dose ranges for various taxonomic groups. (Prepared from data tabulated by Sparrow, A. H., Underbrink, A. G., and Sparrow, R. C., *Radiat. Res.*, 32(4), 915, 1967.)

following catastrophic nuclear accidents or nuclear warfare. However, more subtle yet possibly significant effects, such as impairment of reproduction or growth, can be expected at sublethal doses, roughly in the range of 10 to 100% of the lethal doses. Very low doses, say less than 1% of the lethal doses, are not likely to produce measurable perturbations in populations or communities. At the organism level however, there is a spectrum of probabilistic effects that are unlikely, but possible from such low doses including carcinogenesis, genetic mutations, and lifespan shortening. These effects, while tragic to a very low proportion of the individuals that constitute a population, will not measurably affect populations or communities.

Another idea that clearly emerges from the previous discussion is that the radiation response of an organism in nature can be modified significantly by the nature and condition of the organism, as well as by the biotic and abiotic environment. As a result, laboratory studies have very limited predictive value for judging radiation response of natural populations. Many studies suggest that the rigors of the natural environment may enhance the sensitivity of organisms to ionizing radiation. In other words, some organisms can better tolerate radiation stress in a protected, artificial laboratory environment than in nature where they are also stressed by competition, predation, climatic factors, and so on. On the other hand, some comparatively radioresistant organisms may gain a selective advantage by radiation stress applied to an entire community, dependiug of course on the dose level.

V. CHRONIC IRRADIATION INVESTIGATIONS

The authors will now consider the effects of chronic irradiation at various levels of biological integration. Emphasis will be focused primarily at the community level since, as observed from acute irradiation studies, irradiated organisms in the natural environment do not generally respond independently of other individuals and resulting biotic interactions. In many respects, chronic irradiation studies are more germaine to the question of radiation in the environment than acute studies. For example, fallout from nuclear detonations results in short-term to chronic exposures, as do most radio-

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active effluents. In chronic irradiation situations, dose rate is usually a better predictor of effects than is total dose.

Very rarely have radiation dose rates in the natural environment been sufficient to produce observable effects on the structure or performance of populations and communities. This applies to areas of high natural background radiation, as well as to localities that have been contaminated by the activities of man. As a result, most knowledge on effects of chronic radiation in the environment has been derived from experimental situations, both in the laboratory and in the field. Large, sealed point sources of gamma radiation, such as ^{137}Cs and ^{60}Co have been used, as well as radioactive particulate materials. Most studies on aquatic systems have been conducted in laboratory aquariums.

A. Laboratory Studies

As previously mentioned, there has been considerable interest in the effects of incorporated radionuclides on developing fish eggs. Experimental procedures generally involve placing the eggs, or later developmental stages, in aquatic media containing a radionuclide or mixture of radionuclides. Thus, chronic irradiation may be accomplished by the presence of the radionuclide external to the egg or developmental stage and also from biologically incorporated material. Details concerning various experimental procedures and recommendations for future investigations have been offered by Polikarpov.[64] He mentions the use of single radionuclides, mixtures of radionuclides, and a combination of radionuclides with various chemical compounds or substances. This review also includes methods of external irradiation and lists of parameters that can be measured to judge response. These parameters include the amount of time required for various developmental stages, number of fertilized eggs, egg mortality, abnormalities, and biochemical and physiological characteristics. A comprehensive table of radiobiological investigations of developing eggs in marine, fresh, and brackish water was included. A similar table was prepared by Blaylock and Trabalka[19] that concerns only incorporated radionuclides (Table 9).

In relatively recent years, interest has turned from gross abnormalities of developing eggs to cytogenetic studies. A chapter bearing the title "Radioecological Cytogenetics and Problem of Effect from Small Doses of Ionizing Radiation" appears in *Marine Radioecology*.[126] Tsytsugina, et al.,[127] in their book *Artificial and Natural Radionuclides in Marine Life*, included a similar chapter, "Karyology of Marine Fish and the Effect of Radionuclides on Their Chromosome Apparatus." Discussions include morphology, number, and spontaneous variability of chromosomes. The expected tendency for an increase in cytogenetic effect with increase in dose was observed. In a study of prolarvae of "flounder" reared in a ^{91}Y solution, investigators observed a statistically significant higher percentage of abnormal mitoses in deformed prolarvae as contrasted with those that appeared outwardly normal.[127]

Blaylock[128] reported a study of the production of salivary gland chromosomal aberrations in *Chironomous riparius* larvae of parents cultured in tritiated water. He observed an increase in the frequency of aberrations in larvae whose parents had been raised in 250 and 500 μCi/mℓ of HTO. When the frequency of aberrations of larvae of parents exposed to acute gamma radiation was contrasted with those from parents cultured in HTO, it was observed that they were approximately the same for an equivalent dose. It should be noted that the levels of HTO used in this investigation were 2500 to 5000 times the maximum permissible concentration for occupational exposure.

Considerable interest has developed concerning the effects of tritium on the embryonic development of aquatic organisms. Walden[129] raised fertilized eggs of the three-spine stickleback *(Castorosteus aculeatus)* in 0.5, 1.0, and 2.0 mCi/mℓ concentration of tritium in lake water. He did not observe any morphological anomalies, but at the

Table 9
EFFECTS OF INCORPORATED RADIONUCLIDES ON DEVELOPING FISH EGGS

Radionuclides	Species	Stage exposure commenced	Biological end point	Concentration ($\mu Ci/m\ell$) and observed effects
$^{90}Sr—^{90}Y$	*Engraulis encrasicholus*	Shortly after fertilization	Hatching Growth rate Abnormalities	2×10^{-5}, decreased Retarded 2×10^{-7}, increased
$^{90}Sr—^{90}Y$	*Serranus scriba*	Shortly after fertilization	Hatching Growth rate	2×10^{-5}, no effect 2×10^{-5}, retarded
$^{90}Sr—^{90}Y$	*Salmo trutta*	Immediately after fertilization	Hatching Abnormal larvae	10^{-1} No effect
$^{90}Sr—^{90}Y$	*Pleuronectes platessa*	Immediately after fertilization	Hatching Abnormal larvae	10^{-1} No effect
$^{90}Sr—^{90}Y$	*Scorpaena porcus*	Developing eggs	Chromosome breaks	10^{-6}, increased
^{90}Sr ^{137}Cs	*Salmo salar*	Sixth stage	Death of fry and embryos	5×10^{-6}, ^{90}Sr; 2.5×10^{-6}, ^{137}Cs, increased
$^{90}Sr—^{90}Y$	*Tinca tinca*	Shortly after fertilization	Hatching Abnormalities	1×10^{-2} No effect
$^{90}Sr—^{90}Y$	*Misgurnus fossilis*	Shortly after fertilization	Mortality	1.0, $^{90}Sr—^{90}Y$ No effect
^{137}Cs + $^{90}Sr—^{90}Y$	*Salmo clarki*	—	Abnormalities	10^{-3}, ^{137}Cs + ^{90}Sr + ^{239}Pu
^{239}Pu	*Oncorhynchus gorbuscha*	—	Mitotic index Oxygen consumption	10^{-5}, ^{239}Pu 10^{-1}, $^{90}Sr—^{90}Y$, depressed
$^{90}Sr—^{90}Y$	Caspian salmon	Early stage of development	Mortality —	1.75×10^{-8}, increased —
	Sturgeon		Cytological index	Not significant
	Starred sturgeon		—	—
	White sturgeon		Oxygen consumption	Depressed
	Silver carp			
Fission products ^{131}I, ^{140}Ba, ^{140}La, ^{106}Ru, ^{106}Rh	*Coregonus peled*	Late gastrula	Dead eggs Hatching	Equivalent doses above 500 rad decreased hatching
^{137}Cs, ^{90}Sr, ^{144}Ce	*Dentex canadiensis* *Trachurus trachurus* *Trichiurus lepturus*	Shortly after fertilization	Dead eggs Abnormalities	10^{-2} No effect
$^{90}Sr—^{90}Y$	*Ctenopharyngodon idella*	Shortly after fertilization	Dead eggs Abnormalities	1.10×10^{-3} Increased
$^{144}Ce—^{144}Pr$	*Pimephales promelas*	Gonads and developing eggs	Abnormalities	1.2×10^{-4} No effects
^{238}Pu, ^{232}U	*Cyprinus carpio*	Immediately after fertilization	Hatching	7.5, ^{238}Pu and 5.0, ^{232}U, decreased
			Abnormalities	3.9, ^{238}Pu and 1.2, ^{232}U, increased
^{238}Pu, ^{232}U	*Pimephales promelas*	Blastula	Hatching	1.3, ^{238}Pu and 0.5, ^{232}U, decreased
			Abnormalities	0.26, ^{238}Pu and 0.2, ^{232}U, increased

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Table 9 (continued)
EFFECTS OF INCORPORATED RADIONUCLIDES ON DEVELOPING FISH EGGS

Radionuclides	Species	Stage exposure commenced	Biological end point	Concentration (μCi/mℓ) and observed effects
^{14}C	*Carassius carassius*	8—16 Blastomeres	Hatching	2×10^{-2}, decreased
	Rutilus rutilus		Abnormalities	Increased
	Alburnus alburnus		Mortality	Increased
	Accrina cernua			
^{3}H	*Cyprinus carpio*	Immediately after fertilization	Hatching	518 No effect
^{3}H	*Gasterosteus aculeatus*	Immediately after fertilization	Mortality	2000
			Abnormalities	No effect
			Eye diameter	1000, reduced
^{3}H	*Salmo gairdneri*	Immediately after fertilization	Hatching	10
			Abnormalities	No effects
^{3}H	*Paralichthys olivaceous*	16—cell stage	Hatching	10 No effect
	Fugu niphobles	2-cell stage	Hatching	10 Decreased
^{3}H	*Salmo gairdneri*	6 hr after fertilization	Immune response of fry	1 Suppressed

From Blaylock, B. G. and Trabalka, J. R., *Adv. Radiat. Biol.*, 7, 103, 1978. With permission.

two higher levels there was a significant reduction in the average eye diameter. In a similar study, Strand et al.[130] exposed eggs of rainbow trout to tritium concentrations of 0.01, 0.1, 1.0, and 10.0 μCi/mℓ for 25 days throughout embryogenesis. They observed no significant difference in any treatment regarding proportion of eggs hatching, number of abnormal larvae, or effect on selected behavioral or physiological parameters.

Guppies *(Poecilia reticulata)* were raised in tritiated water throughout embryogenesis by Erickson,[131] who reported that:*

> "Significant effects were an increased proportion of males and an earlier appearance of male sex characters in fish exposed to the lowest HTO concentration used [0.025 mCi/mℓ]. At higher doses, courting intensity and rate of development of male characters were generally depressed. In irradiated male fish, both an increase and decrease in growth was seen; and those exposed to lethal heat stress showed both increased and decreased survival time, depending on the dose. There were no effects seen on the survival of irradiated fish by 90 days following treatment."

Eggs and embryos of aquatic organisms exposed to soluble radionuclides in solution can be expected to sustain enhanced doses to critical structures because of biological incorporation. Less soluble alpha emitters are less effective if the alpha particles cannot reach the nuclear material. Thus, one would expect that high concentrations of such nuclides would be required to produce effects. In a study involving chronic exposure of eggs of the carp minnow *(Cyprinus carpio)* and flathead minnow *(Pimephales pro-*

* From Erickson, R. C., Effects of chronic irradiation by tritiated water on *Poecilia reticulata*, the guppy, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1091.

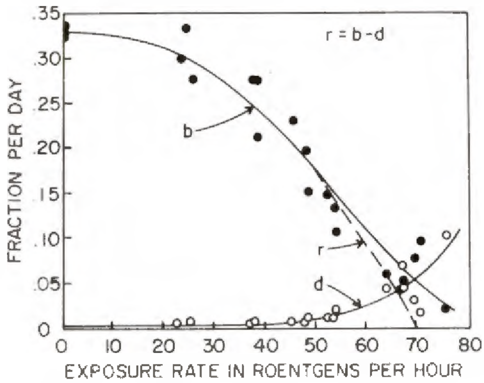

FIGURE 5. The effects of continuous gamma radiation on the population birth rate (dots) and the population death rate (circles) of *Daphnia pulex*. Dashed line represents r, the intrinsic rate of natural increase. (From Marshall, J. S., *Ecology*, 43(4), 598, 1962.)

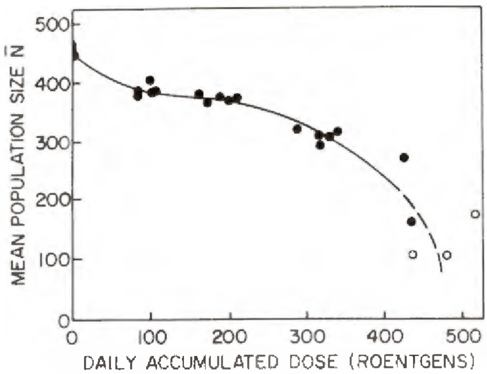

FIGURE 6. Effects of chronic radiation stress on mean population size, $\overline{N}$, of 25 *Daphnia pulex* populations, based on weekly total censuses during a 55-week irradiation period. Open symbols represent populations that became extinct. (After Marshall, J. S., Population dynamics of *Daphnia pulex* as modified by chronic radiation stress, *Ecology*, 47(4), 561, 1966. Copyright 1966 by the Ecological Society of America.)

melas) to ^{238}Pu(IV) citrate, Till observed that concentrations greater than 1 mCi/mℓ were required to prevent hatching of eggs of both species.[132]

Larvae of the Pacific oyster *(Crassostrea gigas)* were chronically exposed to various concentrations of ^{65}Zn, ^{51}Cr, and ^{90}Sr + ^{90}Y in order to determine the amounts required to produce larvae with incompletely developed shells.[133] The exposure period was the first 48 hr after fertilization. It was concluded that: "the concentrations required to produce abnormal oyster larvae are more than a million times greater than the concentration of these radionuclides that have been found in natural environments." This study was motivated by the relatively large amounts of ^{65}Zn and ^{51}Cr introduced into the Columbia River and its estuary as a result of the operation of the production reactors at

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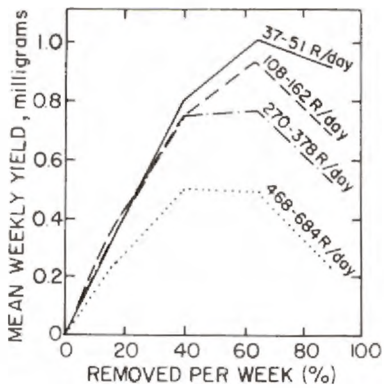

FIGURE 7. Effects of exploitation on mean weekly biomass yield from *Daphnia pulex* populations at four different levels of chronic radiation stress. (After Marshall, J. S., *Limnol. Oceanogr.*, 12(1), 154, 1967. With permission.)

In addition to embryonic forms of aquatic organisms, the adult form has been chronically irradiated. Chinook salmon *(Oncorhynchus tshawytscha)* smolts were exposed to gamma radiation from a ^{60}Co source at 0.5 to 50 R/day.[134] Sex ratios were unaffected by 5 R/day or less, while at 10 or more R/day, gonadal development was retarded. Mosquito fish *(Gambusia affinis)* were also exposed to gamma rays from a ^{60}Co source.[135] Acute irradiation of 750 to 6000 rad or chronic irradiation at dose rates of 1.3, 2.5, or 5.4 rad/hr for up to 47 days was administered to fish maintained at either of two temperatures, 15 or 25°C. Mortality exceeded the controls only for acute irradiation of 5800 to 6000 rad. Although some fish accumulated doses over 5000 rad in the chronic irradiation study, mortality at all dose levels failed to exceed that of the control. In both acute and chronic irradiation studies, testis atrophy was observed at all doses.

Populations of animals have been chronically irradiated in the laboratory in order to observe response of parameters that influence population dynamics. Such parameters include mortality, life span, reproductive success, sex ratios, and time of sexual maturity. Population response to changes in these parameters may affect performance directly, or indirectly by altering interactions such as competition and predation. Blaylock[76] observed that when two competitive fruit fly species, *(Drosophila melanogaster)* and *(D. simulans)* were chronically irradiated, that, although *D. simulans* was the superior survivor in the control for a period of 30 weeks, *D. melanogaster* eliminated this species when the two were exposed to a dose rate of 4.3 rad/hr. At an acute dose of 2000 rad, *D. melanogaster* was superior to *D. simulans*, with the latter being superior at 10,000 rad. Even though population size was affected by irradiation, most of the population recovered 6 weeks after initiation of the experiment.

In a classic experiment involving *Daphinia pulex*, Marshall[136] measured the effects of chronic gamma radiation from ^{60}Co on the actuarial parameters: b (birth rate), d (death rate), and r (intrinsic rate of natural increase). The data indicated a reduction in birth rate beginning at exposures of about 20 R/hr, with increases in death rate beginning at around 50 R/hr (Figure 5). At 70 R/hr, birth and death rates were the same value and r was, therefore, zero. This experiment was probably the first to measure the effects of radiation on the basic parameters describing the dynamics of natural populations.

In a second experiment, Marshall[137] exposed *Daphnia pulex* populations to measure effects on actual population size. Exposure rates ranged from 0 to 516 R/day, with the populations being exposed for 18.5 hr/day for a period of 55 weeks. At high exposures the population became extinct, but at the lower levels it was observed that the mean population size decreased with daily accumulated dose (Figure 6). As there appeared to be an inverse relationship between mean population size and mean turnover rate, Marshall concluded that net production might be less affected by ionizing radiation: *

"Radiation stress became a limiting factor for population size and turnover rate at much lower dose rates than those needed to limit net production. Within the entire range of indefinitely tolerable dose rates, the population consequences of radiation stress stem almost entirely from effects on individual fertility and survival, whereas individual metabolism is apparently unaffected. Increased individual growth is an indirect effect, due to reduced fecundity at a given food supply per individual or increased food consumption at a given food supply per population."

In a later investigation, Marshall[138] was interested in the relationship of chronic radiation stress to exploitation of the laboratory populations. He established four exploitation rates (15, 40, 65, and 90% of the population per week) at each of four dose levels. At all levels of irradiation Marshall observed an initial increase in biomass production and then a decrease with increasing rate of exploitation (Figure 7). He concluded that the exploitation increases the effect of radiation stress and that "...the yield depression is greater and more progressive as radiation levels increase at the higher exploitation rates." A decrease in average individual weights with increasing exploitation was observed, which was evidence for an increase in population turnover. This study indicated to the author that "the amelioration by exploitation means that exploitation tends to make populations (not individuals) more resistant to the effects of radiation."

In an attempt to evaluate the effects of chronic irradiation on sessile marine invertebrates, Williams and Murdoch[139] developed a procedure in which organisms were placed in running water and exposed to radiation from a ^{60}Co source for at least 94% of the time over a period of approximately 3 to 7 months. They selected ten dose rates (8.5×10^{-6} to 21.2 rad/hr) for the experiment. New tissue growth of sponge, *Hymenacidon heliophila*, was reduced at dose rates as low as 0.85 rad/hr; coral, *Astrangia* spp., was damaged at 4.2 rad/hr; growth and survival of oysters, *Crassostrea virginica*, was slightly reduced at 4.2 rad/hr; and at 8.5 and 1.7 rad/hr, respectively, slipper shells, *Crepidula fornicata*, and ascidians, *Molgula manhattensis*, grew normally. Decreased respiration was observed in sponges at higher dose rates. These experiments suggested a difference in radiosensitivity among marine invertebrates exposed to chronic irradiation; however, for the species investigated, there was no relationship of sensitivity to phylogeny — the most primitive organism (sponge) was the most sensitive. The authors concluded, "our experiments do suggest that some marine invertebrates may be damaged by a chronic irradiation of less than a rad/hr and that others are far less sensitive." Using the same experimental setup, microcosms of sediment, algae, and invertebrates were given maximum dose rates of 2.1 to 3.3 rad/hr for a year, but no clear-cut effects were observed.[140]

Chronic irradiation investigations with wild rodents maintained in a laboratory appear to be restricted to the investigations of French,[70] French and Kaaz,[141] and Sacher and Staffeldt.[102] French established a laboratory population of deer mice *(Peromyscus maniculatus)* by providing shelters consisting of coffee cans and on top of each was

* From Marshall, J. S., Population dynamics of *Daphnia pulex* as modified by chronic radiation stress, *Ecology*, 47(4), 561, 1966. With permission.

placed a 1 mCi ^{137}Cs source. Thermoluminescent dosimeters attached to individuals recorded an average of 1.23 R/day exposure, with a range from 0.8 to 2.9 R/day. Data on survival and natality were utilized in computing the intrinsic rate of increase for the control and irradiated populations. This statistic was computed as 0.1897 and 0.3134 for irradiated and for control populations, respectively.[70] Life shortening was observed in both sexes of the irradiated populations when contrasted with the controls. An intrinsic rate of increase of 0.3574 for a population, irradiated only as adults was observed, as contrasted with the value of 0.1897 for the population irradiated since conception.[141]

Sacher and Staffeldt[102] investigated life spans of several small rodent species exposed daily to gamma rays, commencing at the "young adult stage". Thirteen species were being investigated at the time of this report and not all studies had been completed. However, the investigators resported that the California mouse *(Peromyscus californicus)* and rice rat *(Orysomys palustris)* were "...extremely radiosensitive at all levels from 12 to 125 R/day" and that some species were relatively resistant to chronic irradiation, with others being intermediate. At dose rates of 24 to 125 R/day, female rodents were more radiosensitive than males.

Investigations that might be considered "semilaboratory" were reported for irradiated plant communities by McCormick and Platt[142] and by Garrett.[143] These investigators transplanted intact "island communities" from a granite outcrop in Georgia to a gamma radiation field at Emory University.[62] The natural transplanted plant community was exposed at rates of 5 to 82 R/hr for total exposures ranging from 8000 to 130,000 R.[142] Immediate and long-range effects were observed on individual species and on various community attributes. It was concluded: "results indicate that ionizing radiation has both stimulatory and inhibitory effects upon plant growth and that the ecological and morphological effects are reflected by species interactions at the community level."

Garrett[143] was interested in the plant and the soil arthropod communities on the transplanted granite outcrop ecosystems. He evaluated the effects of chronic irradiation by comparing various measures of similarity and diversity throughout the exposure period. Diversity of soil arthropod samples decreased with increasing radiation exposure and the similarity index for plant samples also decreased. He concluded that such decreases were probably attributable to a combination of factors, including ionizing radiation. Of interest is the comment: "the results of the present investigation suggest that no single index can be applied to every situation and that indexes which drastically reduce the details of data are not completely satisfactory replacements for detailed ecological observations."

B. Field Investigations

Although considerable difficulty is associated with field investigations of natural biotic communities, radiation ecologists have attempted to overcome the inadequacies of laboratory data by conducting studies in areas of high natural radiation background, in waste disposal areas, in field plots contaminated artificially with radionuclides, or by placing a large gamma radiation source within an ecosystem. General comments concerning these approaches were presented at the beginning of this chapter. The authors will now consider the results of some representative investigations, particularly those utilizing a large radiation source in the field.

1. High Natural Background Areas

In addition to the previously cited references of Gruneberg et al.,[46] Drew and Eisenbud,[45] Verkhovskaya,[47] and Cullen and Penna Franca,[48] there are other investigations of note on both plants and animals. One type of investigation is aimed at deducing

whether or not chronic exposures to natural background radiation conditions organisms to radiation stress at higher levels. For example, aquatic isopod *(Lirceus fontinalis)* populations on a granitic area of Georgia with slightly elevated levels of radiation and a control population were exposed to acute gamma radiation, various temperatures, and drought conditions.[144] The investigator observed a higher resistance to radiation and drought in the granitic populations as contrasted to the control. It was tempting to infer that chronic exposure to elevated natural radiation conferred a degree of radioresistance, but other possible causal factors could not be ruled out. Kratz[145] studied the radioresistance of the fruit fly, *Drosophila nebulosa*, collected from both a control area and an area of high natural background in Brazil with the conclusion that the latter were more resistant than the control population.

Looking for other influences of natural radiation, Verkhovskaya et al.[146] investigated tundra voles *(Microtus oeconomus)* living on a uranium area with a radiation level about two orders of magnitude higher than surrounding areas. Sex glands of males evidenced damage, the degree of which was directly related to the level of incorporated radionuclides as well as the total radiation dose. Blood plasma characteristics were also studied in these animals by Aliyev and co-workers.[147-149] Although no significant deviations from normal in amino acid composition in blood plasma proteins were detected, deviations were observed in morphology of red blood cells, total protein content, and other characteristics.

Osburn[150] observed a greater incidence of morphological variations in *Penstemon* growing on an area of higher natural radiation background than plants from a nearby control area. However, the possible effect of higher radiation level was confounded with other ecological variables. In a follow-up investigation, Mericle and Mericle[151] introduced *Tradescantia* in pots into the high radioactivity area (0.25 mR/hr) and a nearby control area. The clone of this particular plant which was used is not only very radiosensitive, but somatic mutations are easily scored by color variations in petals and stamen hairs.[152] It was noted that: "...the frequency of mutant sectors increased four- to fivefold and that of morphological anomalies of the floral apparatus rose nearly ninefold". This is one of the only investigations in which an unequivocal biological response to natural background radiation has been observed. In a similar study, investigators utilized *Tradescantia* on a monazite sand area in India.[153] In an investigation of natural plants on the same area, the incidence of meiotic abnormalities in plants from the high natural radiation area was greater than in the control plants and the computed total dose received by the plants was correlated with the incidence of abnormalities.[154]

Natural populations of a liverwort *(Marchantia polymorpha)* and moss *(Pogonatum urnigerum)*, growing on an area of high natural radioactivity in Poland, were studied in various microhabitats differing in gamma radiation levels.[155-156] In the exposure range 0.13 to 0.18 mR/hr no response to radiation was observed; in the range 0.76 to 0.91 mR/hr vegetative growth was stimulated — area of thallus larger, gemmulae growth and production greater. At this higher exposure range, sexual development was inhibited and only "pure ecological populations" of the liverwort existed, while at the lower range other species of bryophytes competed successfully with *M. polymorpha*.[155] According to the investigators:[156] "it was demonstrated that radiation within the above mentioned range (0.05 to 0.91 mR/hr) is an essential ecological factor conditioning the ecotype differences in *Pogonatum urnigerum*, and among them the developmental anomalies." This study is typical of many, in that, while differences in biological structure or function between areas of differing radiation level are observed, the causal inferences are at best, speculative.

2. Waste Disposal Areas

Perhaps the most intensive investigations of radiation effects on wild animals inhab-

iting waste disposal areas are associated with White Oak Lake and its basin, located at the Oak Ridge National Laboratory. This lake of approximately 40 acres was created in 1943 by impounding the waters of White Oak Creek; it was partially drained in 1955 and later was partially refilled. It was constructed to serve as a disposal site for liquid waste (radioactive, chemical, and primary-treated sewage) from the laboratory.

Initial ecological efforts included studies on the accumulation of radionuclides by fish as reported by Krumholz.[50] It was estimated that the total dose received by fish in the lake was 57 Rep (roentgen equivalent physical) per year externally and probably several times this internally:*

"As a result of this irradiation, it is believed that the fish population of White Oak Lake may have suffered deleterious effects, as manifested by the shortened life span, the slow growth rate, and possibly the decreased fertility of the breeding stock of the redhorse [*Moxostoma erythrurum]*."

Following draining and partial filling of White Oak Lake, Blaylock[53] compared the fecundity of the common mosquito fish *(Gambusia affinis affinis)* in the lake with that of a control population. The history of the lake population involved 100 generations and the control was effectively separated from the lake population in an impounded tributary to White Oak Creek for more than 20 generations. It was estimated that the dose received by the White Oak Lake population was 10.9 rad/day (later revised to 350 rad/day). Blaylock reported a significantly larger brood size and more dead embryos and abnormalities in the White Oak Lake population than in the control population. He suggested that the increase in fecundity is a means of adjustment of the population to mortality caused by radiation.

Chromosomal polymorphism in midge larvae, *Chironomus tentans*, collected from the radioactive bottom sediments of White Oak Creek was also compared with a control population.[157] Although there was an increase in new chromosome aberration frequency in larvae from the contaminated stream population, "... the frequencies of the endemic inversions were not changed by chronic radiation". It was also stated:**

"It was concluded that the occurrence of new aberrations in the White Oak Creek population was increased by the high background radiation level, and that these new aberrations were rapidly eliminated by selection or genetic drift."

During the period that the lake bed was exposed, Dunaway and Kaye[51] studied cotton rats utilizing the lake bed and those from a control area. It was estimated that the animals were exposed to about 0.4 R/day on the lake bed. Captured animals were examined for pathologic lesions, litter size, and sex ratios, but no effects attributable to radiation were found.

In recent years, nuclear waste disposal areas at Hanford and the Idaho National Engineering Laboratory have begun to receive increased study from the standpoint of possible biological effects from radioactivity. There are several ponds, ditches, and trenches on the Hanford Reservation which have received liquid radioactive wastes from nuclear facilities.[158] All these systems, with possible exception of the 100-N trench, support apparently normal populations of aquatic biota, and there is no conclusive evidence of ecological effects from radiation. At the Idaho National Engineering Laboratory site, a radioactive leaching pond at the Test Reactor Area and a radioactive solid waste burial site have been investigated to determine possible systemic effects of radiation on rodents.[159] Deer mice *(Peromyscus maniculatus)* that received

* From Krumholz, L. A., Observations on the fish population of a lake contaminated by radioactive wastes, *Bull. Am. Mus. Nat. Hist.*, 110(art. 4), 277, 1956. With permission.

** From Blaylock, B. G., Chromosomal aberrations in a natural population of *Chironomus tentans* exposed to chronic low-level radiation, *Evolution*, 13(3), 421, 1965. With permission.

measured dose rates up to about 1 rem/day at the leaching pond failed to exhibit any evidence of blood changes or pathologic lesions such as solid tumors. However, deer mice at the solid radioactive waste burial site showed statistically significant evidence of blood changes, such as depression of red blood cell count, hemoglobin, white cell count, and mean cell volume. Dose estimates were in progress for the latter population.

3. Simulated Fallout Studies

In a continuation of research which had been conducted at the Emory University radiation field on the response of granite-outcrop plant communities, Murphy and McCormick[60] designed concrete circular depressions on which transplanted communities were placed. Sodium feldspar particles containing the beta emitter ^{90}Y were used to simulate fallout particles. Sufficient quantities of the simulant were placed on the communities to provide dose levels at which effects were previously observed from chronic gamma irradiation. The average dose to the plant communities was 4000 and 7000 rad in a period of 33 days. Most of the dose was delivered during first 10 days, owing to the 64 hr half-life of ^{90}Y. Metabolism of the communities was studied by measurement of CO_2 exchange, with the result that no changes were observed. Mortality of the terminal buds and reduction of height growth was observed in the dominant plant *Viguiera porteri* with some compensatory lateral branch development. At equivalent total doses, short-term beta irradiation appeared to be twice as effective as chronic gamma irradiation in producing growth reduction.

Eight 100-m^2 enclosures were constructed on fescue meadow at Oak Ridge National Laboratory of which four were contaminated with ^{137}Cs-labeled sand and four were used as controls.[160] The study was designed to evaluate the effects of chronic gamma irradiation from an important constituent of fallout on components of the grassland community. Using thermoluminescent microdosimeters to measure dose rates to an arthropod community in the enclosures, Styron and colleagues[161] studied the effects of ionizing radiation on similarity and diversity indexes. Although differences were observed, they were not lasting and could not be attributed to ionizing radiation. The authors concluded:*

"...the apparent threshold for mixed beta and gamma radiation inducing changes in community structure must be above the exposure rate range of 2.3 to 13 rad/day delivered during the 5 yr observation."

In the same enclosures, DiGregorio and co-workers[59] studied cotton rat populations. Accumulation of ^{137}Cs in soil, plants, and various organs and tissues of the cotton rat were determined. Toshiba fluoro glass dosimeters were used to determine the in vivo gamma dose. The average dose rate to the animals ranged from 2.35 to 3.84 rad/day. No effects of ionizing radiation on body weight or peripheral blood were observed.

Simulated fallout studies have not been restricted to the U.S. Scientists in the U.S.S.R. have also conducted such investigations. For example, Aleksakhin and colleagues[162] sprayed ^{90}Sr on the soil surface in order to study the accumulation by conifer seedlings of the soil-incorporated ^{90}Sr. These investigators also reviewed research in the U.S.S.R. utilizing spray application of ^{89}Sr ($\geqslant$ 8 mCi/m^2) on white pine *(Pinus sylvestris)*. Photodosimeters were placed within the crown to measure beta radiation dose. Drying of needles and of current sprouts were observed when a dose of 2000 rad had been delivered. Double sprouting was observed from 300 to 1200 rad. Studies on the effects of soil surface application of ^{90}Sr + ^{90}Y and ^{137}Cs on seeds and seedlings of various conifers are also described. Cytogenetic studies of natural populations of

* From Styron, C. E., Dodson, G. J., Beauchamp, J. J., and Miller, F. L., Jr., *Radioecology and Energy Resources*, Cushing, C. E., Jr. et al., Eds., Dowden, Hutchinson & Ross, Stroudsburg, Pa., 1976, 381. With permission.

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Vicia cracca and *Agrimonia eupatoria* exposed to increased levels of ^{90}Sr, which were apparently produced experimentally, were reported by Cherezhanova and Aleksakhim.[163]

Fallout simulation experiments involving animals in the U.S.S.R. have also been conducted. Field plots were contaminated with ^{90}Sr and the degree of infestation by gamasid ticks of four small mammals dwelling on these plots was investigated by Il'yenko[164] with the conclusion:*

"Among the adults the intensity of infestation and indices of abundance of mites on animals increased with the concentration of ^{90}Sr and the dose of ionizing irradiation."

Isaev[165] studied the wood mouse *(Mus silvaticus)* on each of two control plots and two plots contaminated artificially with ^{90}Sr at levels of 0.01 to 1.2 mCi/m^2. He observed effects of ionizing radiation on fertility and embryonic mortality.

4. *Large Gamma Point Sources*

In this section some of the findings of field experiments involving chronic gamma irradiation from large point sources listed in Table 3 will be discussed. Except for the relatively recent studies on the effects of gamma radiation on a northern forest ecosystem,[166] the results of such studies have been summarized for plant communities by Whicker and Fraley[17] and for animal populations by Turner.[18] The reader is directed to these reviews as well as to the original publications for much more detail than we are able to present here.

A fundamental feature of communities which explains many of the changes observed following irradiation is the widely varying radiosensitivities of different organisms. Some species exhibit lethality at acute exposures less than 0.5 kR, while other species are extremely resistant with acute exposures of 100 kR or greater required to produce lethality. A similarly wide range of sensitivity exists for other end points of radiation damage. In general, lasting radiation-induced genetic effects in natural communities have not been observed; thus, we shall not consider such effects. We will instead focus upon changes in structure and function of populations and communities which result from somatic effects upon the generation irradiated, with some consideration to recovery of radiation-stressed systems following exposure.

a. *Plant Communities*

The number of methods used for the study of structure and function in natural communities is far too large to cover here, but a few general remarks seem justified. Among the community characteristics which have been measured in relation to the stress of ionizing radiation are physiognomy (plant growth/form), vegetative cover, species composition, diversity, and respiration. At the population level, characteristics such as density or frequency of occurrence, growth and vigor, reproduction, mortality, phenology, and morphology are often measured. Study of component populations and of individuals within such populations can give the investigator significantly greater insight into changes at the community level than one can obtain from community attributes alone. Each population and community attribute mentioned normally varies in time according to temporal cycles or progressions. An understanding of such temporal phenomena is necessary in order to facilitate interpretation of radiation effects.

The study of form and structure in natural communities is called "physiognomy". Most studies of irradiated plant communities demonstrate a clear relationship between physiognomy and radiosensitivity. Physiognomy is determined largely by the existing growth-forms of plants in the community. Major growth-forms on land include trees

* From Il'yenko, A. I., [illegible] 5[illegible], 197[illegible]. With permission.

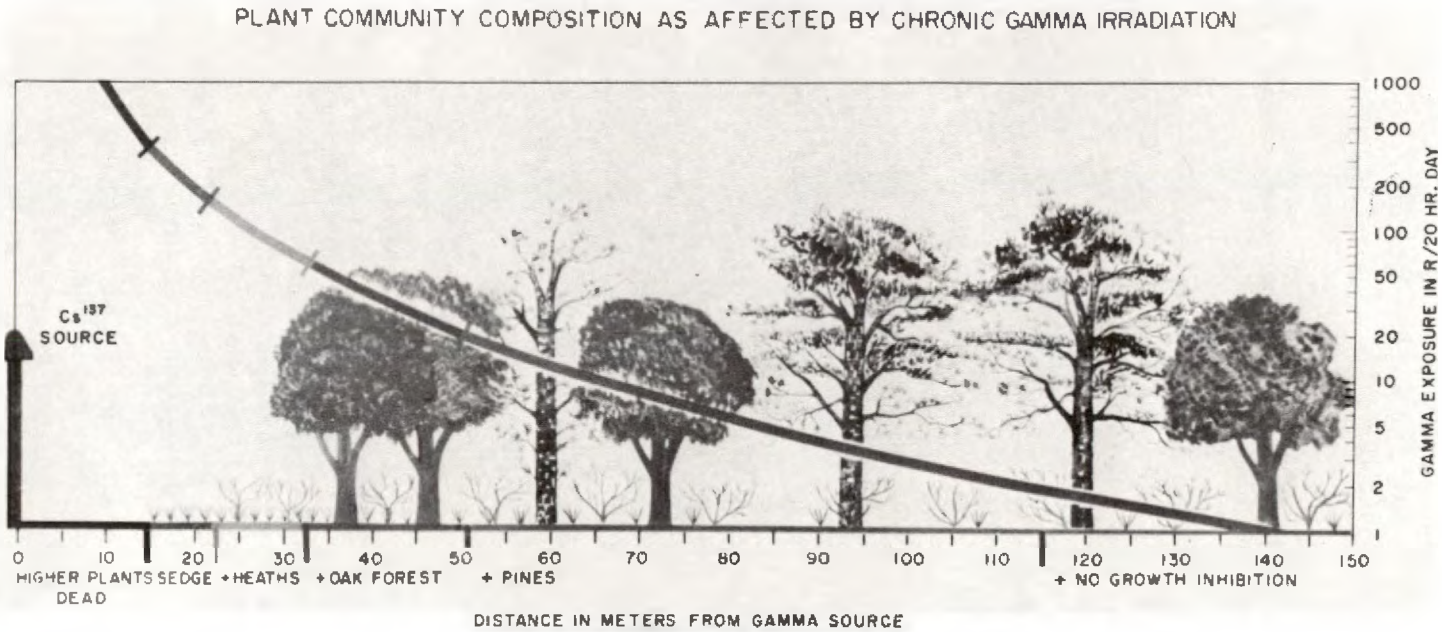

FIGURE 8. Pattern of radiation damage to an Oak-Pine Forest, after about 6 months of chronic exposure. (After Woodwell, G. M., *Science*, 156, 461—470, 28 April 1967. Copyright 1967 by the American Association for the Advancement of Science.)

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of several types, shrubs which are woody but of smaller stature than trees, epiphytes that grow on other plants, herbs that include ferns, grasses, sedges, and forbs, thallophytes that include lichens, mosses and liverworts, and microflora such as bacteria, actinomycetes, and fungi. For example, Woodwell's study on effects of chronic gamma irradiation on an oak-pine forest at Brookhaven National Laboratory supports the idea that simple, low-stature plants can tolerate more radiation stress than the more complex, taller plants.[167] Figure 8 illustrates how radiation selectively killed larger plants, leaving the smaller forms to persist at the higher exposure levels. Data clearly indicated trees as the most sensitive vascular growth form, followed by shrubs and then by an herbaceous form.[168] Further, in the same forest in an exposure rate zone where all vascular plants had been killed, lichen species still survived.[169] Even within the lichen community, the lowest-stature forms (crustose) were more resistant than the higher-stature forms (fruticose and foliose).[170] Forest mosses and liverworts apparently display a rather wide range of tolerance to chronic gamma radiation, but in general they seem to fall in a sensitivity range somewhere between that of lichens and vascular plants.[171] Some species of soil microfungi were growing at exposures in excess of several kR per day after 8 years of continuous exposure[172-173] and changes in soil algae populations occurred only in the "devastated zone".[174]

Effects of various short-term (15 to 90 days) neutron-gamma exposures from an air-shielded reactor on plant communities in the northern Georgia piedmont at various successional stages were summarized by Platt[175] (Figure 9). With minor quantitative differences, effects depicted are probably representative for deciduous forests or preforest seral stages characteristic of much of the eastern U.S. This study also demonstrated increased radiosensitivity with plant stature, and in addition, showed that the higher successional stages could be reverted to earlier seral stages under the stress of radiation. In the vicinity of the reactor, changes in soil microflora were more related to other environmental conditions than to the total neutron-gamma dose received.[176]

Studies under the direction of H. T. Odum on effects of short-term (3 months) gamma irradiation on the El Verde rain forest in eastern Puerto Rico led to numerous findings in relation to a highly structured ecosystem. According to Desmarais and Helmuth,[177] significant physiognomic changes were observed following the 3-month radiation exposure of the rain forest, with important changes including structural simplification, reduction in understory vegetation, and a marked increase in crownless plants within a 12-m radius of the source (total dosages generally >30 krad). Smith[178] found that within canopy tree species, the "primary" species (species more able to penetrate the forest to the canopy) were more sensitive than "secondary" species. Witkamp[179] studied the soil microflora of rock-shielded and exposed sites along a transect extending 3 to 140 m from the radiation source and could not detect any direct effects of ionizing radiation on the microflora 3, 7, and 13 months after irradiation. However, 1 year after irradiation it was observed that bacterial densities and activities in the defoliated area had dropped below that in the forest with leaves remaining. It was presumed that this decrease was the result of "substrate exhaustion" and lack of additional litter deposition. Microfungal populations observed at the site were significantly higher at the source center after irradiation than in the control area.[180]

A ^{137}Cs source was used to chronically irradiate a Mediterranean phytocenose consisting of mixed vegetation, trees and scrubby growth, as well as vegetated clearings.[181] With respect to physiognomic influence on radiosensitivity, it was observed that typical Mediterranean species were more resistant, while submediterranean species were more sensitive. Lichens exhibited increased growth in areas where higher plants sustained significant damage. Various morphological modifications were noted in higher vegetation exposed to sublethal doses. In the same experiment, it was observed that leaf decay was increased by ionizing radiation with an increase in release of organic compounds and mineral elements.[182]

AIR DOSE IN RADS, 15-90 DAYS	DEVELOPMENTAL STAGES								
	HERB			SHRUB					TREE
	YEAR OF DEVELOPMENT								
	YEAR ABANDONED	1st	2nd	3rd	4th	5th	7th-12th PINE	12th-50th DOMINATION	OAK HICKORY PINE CLIMAX
0-1000	MINOR EFFECTS			SOME DAMAGE TO PINE					
1,000-3,000									
3,000-6,000				PINE SEEDLINGS KILLED			PINE KILLED, HARDWOODS RELEASED, SUCCESSION ACCELERATED		PINE KILLED
6,000-10,000	SHIFT IN DOMINANCE								
10,000-20,000				HARDWOOD SEEDLINGS KILLED			HARDWOODS KILLED; REVERSION BY SPROUTS TO HARDWOOD SEEDLING STAGE		
20,000-50,000									
50,000-100,000				REVERSION TO EARLIER HERB STAGE			ALL TREES KILLED, REVERSION TO HERB STAGE		
100,000-300,000									
>300,000	MIXTURE FROM WELL-SHIELDED SEEDS, CORMS, ETC.								

FIGURE 9. Summary of general effects of short-term neutron-γ-irradiation on various successional stages of natural vegetation in the southeastern U.S. Based on studies by Emory University on vegetation surrounding an unshielded nuclear reactor near Dawsonville, Ga. (From Platt, R. B., Ionizing radiation and homeostasis of ecosystems, in Ecological Effects of Nuclear War, U.S. AEC Rep. BNL 917(C-43), Woodwell, G. M., Ed., Brookhaven National Laboratory, Upton, Long Island, N.Y., 1965, 39.)

After 3 years of continuous gamma irradiation of a shortgrass plains community in Colorado, it was evident that the most resistant plant species were herbaceous (Figure 10).[183] Shrubs were generally the most sensitive plants, however, certain herbs were as sensitive as the shrub species. Certain herbaceous species were also the most resistant plants to seasonal 30-day exposures.[184] Soil microflora were present in plots which had received sufficient chronic gamma irradiation to kill all vascular species.[185]

Chronic gamma irradiation of a northern deciduous forest ecosystem at Rhinelander, Wis., resulted in further verification concerning radiation tolerance of plants as related to stature.[186] It was observed that this forest was more radiation resistant than the oak-pine forest at Brookhaven National Laboratory and similar in resistance to the tropical rain forest in Puerto Rico.

Based upon the studies reviewed, the order of radiosensitivity of several common plant growth-forms tends to be trees > shrubs > herbs > thallophytes > microflora. In an irradiated plant community containing several growth-forms, a sufficient dose will tend to favor the survival (or invasion) of herbs and possibly thallophytes and preferentially diminish shrub or tree components.

At sufficient levels of radiation, irradiated plant communities exhibit changes in composition. Community composition usually refers to the aggregate of species populations which exist within the community. Community composition is usually meas-

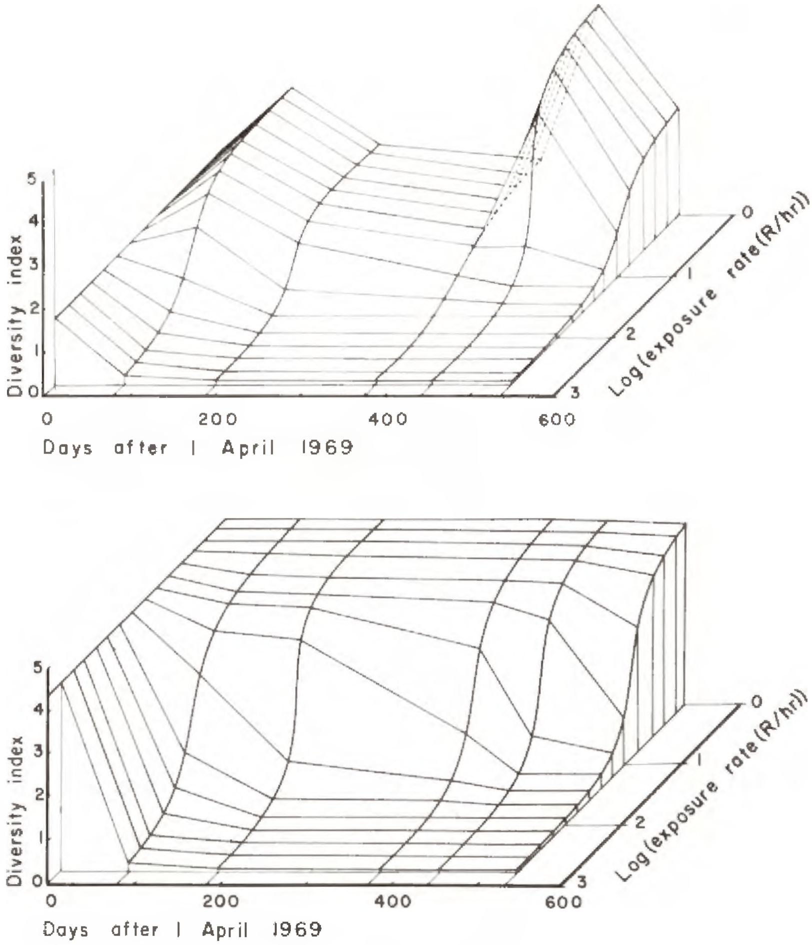

FIGURE 10. Diversity index in a shortgrass plains vegetation stand in north-central Colorado in response to chronic γ-ray exposure rate and time of exposure. Upper figure shows the nonnormalized response; lower figure shows seasonally normalized response. (Reprinted with permission from *Radiat. Bot.*, 13(6), Fraley, L., Jr., and Whicker, F. W., Response of shortgrass plains vegetation to gamma radiation. I. Chronic irradiation. Copyright 1973, Pergamon Press, Ltd.)

ured by comparison to the pre-stressed or control community composition. Under chronic irradiation stress, community composition becomes progressively dissimilar to the original community with increasing time and radiation intensity.[143,168,183,187] Such dissimilarity arises from differential mortality and shifts in numerical importance of species. Differential mortality and shifts in quantitative importance result from intrinsic species differences in radiosensitivity and varied ability of different populations to exploit altered environmental conditions.

Short-term exposures cause effects on community composition that are similar to effects produced under chronic irradiation stress. However, the nature and degree of such effects are dependent upon season of year and physiological state of the system during irradiation. Other important considerations are dose rate, total dose, and extrinsic climatic variables. Additionally, recovery or revegetation may take place while the primary radiation effects are still becoming manifest. Thus, post-exposure observations on community composition can be expected to yield time-variable results.

Following a number of short-term bursts of neutron-gamma irradiation from the

air-shielded reactor in Georgia, Daniel[188] observed significant changes in old-field community composition at a dose of 5500 rad. The degree of dissimilarity between control and irradiated plots appeared to increase at higher dosages. Sufficient doses of radiation tended to slow, stabilize or even reverse the normal pattern of plant succession.[188,189] Comparing composition of a pre- and post-irradiated old-field in South Carolina, Monk[190] observed significant changes in floristic composition with dose. A 50% reduction in a similarity index was observed at 530 R/day.

Diversity, which measures another aspect of community structure, namely richness (or number) of species, is also used to describe radiation response at the community level. Diversity is a measure of the structural complexity of an ecosystem and may be related to ecosystem stability. This relationship is based on the premise that the greater the species diversity, the greater is the potential for alternative functional relationships, the greater is the "protective structure" of the ecosystem, and the more readily the system as a whole can adjust to short-term stresses and perturbations.

Depending upon the way it is calculated, a reduction of diversity in response to stress may imply a loss of species. Woodwell and Oosting[187] reported severe reductions in old-field diversity at a chronic exposure rate of around 1000 R/day. Woodwell and Rebuck[168] found a similar reduction in diversity in the chronically irradiated oak-pine forest, but at a much lower exposure rate (about 100 R/day). In general, a diversity response curve to irradiation is characterized by a more or less definable threshold, above which diversity decreases rather linearly with the logarithm of radiation exposure until a value of zero (complete mortality) is reached. Monk[190] obtained such a diversity response for old-field vegetation as did Miller[191] in old fields receiving seasonal short-term exposures. Diversity decreased with both time and exposure rate in a grassland ecosystem,[17,183] and additionally, a seasonal response due to short-term appearance of annual plant species was apparent (Figure 10).

Nearly all planned experiments on effects of radiation on higher plant communities have demonstrated a reduction in diversity or structural complexity at some exposure level. There was some indication that such was not necessarily the case for a tropical rain forest in Puerto Rico,[192] although perhaps the duration and/or intensity of radiation was insufficient to produce such an effect. Reduction in species diversity with irradiation has been observed in lower as well as in higher plant communities. In the oak-pine forest at Brookhaven National Laboratory, reductions in species diversity with increasing exposure rate were demonstrated for bryophytes,[171] lichens, [170] and soil microfungi.[172]

Ionizing radiation may alter productivity as well as structure in a plant community. Productivity is a functional attribute which describes the rate at which organic material is created per unit area. Significant reductions in productivity may occur at considerably lower levels of radiation stress than would be required to alter community composition or diversity. For example, shoot growth reduction in pitch pines has been observed at exposures down to the 1 R/day range[193] (Figure 11). Ring widths in the same pines were also reduced at exposure rates of 1 to 5 R/day.[194] Other indicators of alterations in productivity at sublethal exposures include reduced net photosynthesis,[195] and reduced litter production.[196-198]

Some investigations have suggested that lower levels of ionizing radiation can produce stimulatory responses in productivity. For example, the data of McCormick and Platt[142] on granite outcrop communities showed increased vigor of irradiated *Arenaria brevifolia* over controls. Likewise, Woodwell and Oosting[187] demonstrated increased standing crop in *Digitaria* with chronic exposure rate (Figure 12). These sorts of "stimulatory" effects, when observed in irradiated communities, more likely reflect a competitive advantage secured by a more resistant species than true stimulation by radiation exposure. Along these same lines, Zavitkovski and Salmonson[199] observed

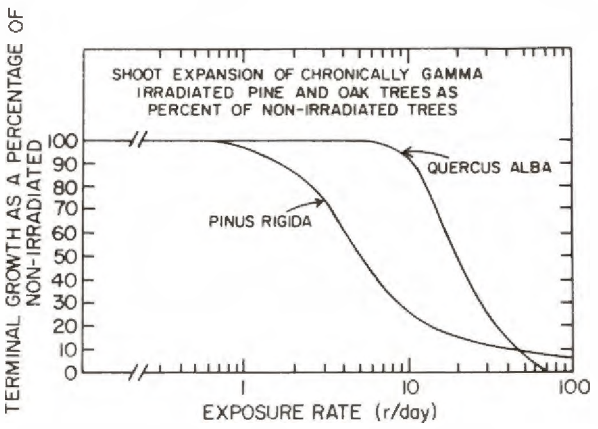

FIGURE 11. Growth of white oak *(Quercus alba)* and pitch pine *(Pinus rigida)* in an irradiated forest, at various rates of exposure. (After Woodwell, J. S., *Science*, 138, 572—577, 2 November 1962. Copyright 1962 by the American Association for the Advancement of Science.)

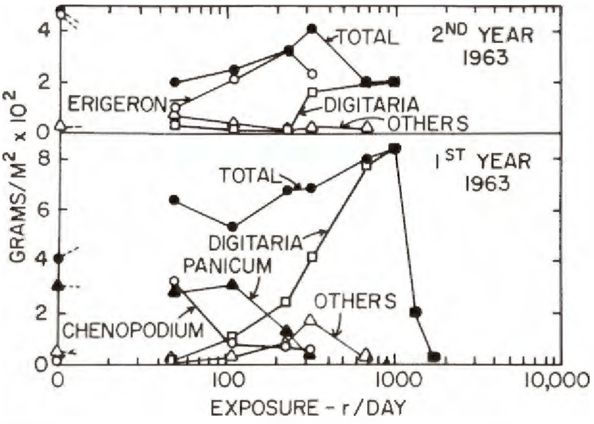

FIGURE 12. Biomass of plant populations in first and second year irradiated old-field communities. (Reprinted with permission from *Radiat. Bot.*, 5(3), Woodwell, G. M. and Oosting, J. K., Effects of chronic irradiation on the development of old-field plant communities. Copyright 1965, Pergamon Press, Ltd.)

increased biomass production of ground vegetation in response to increased light penetration caused by tree mortality.

Biomass reductions in response to radiation exposure have been commonly observed. For example, Monk[190] observed reductions in root biomass with exposure rate in his old-field study. Such an observation could be explained on the basis of direct effects on the roots, as well as decreased production of photosynthate. Fraley[200] observed a general reduction in community biomass under chronic exposure, but a variable response following short-term exposure, depending on exposure level and season of exposure (Figure 13). The large biomass increases following short-term exposures were due to high vigor of invading species in heavily damaged exposure zones.

In summary, total community productivity normally declines with increases in ion-

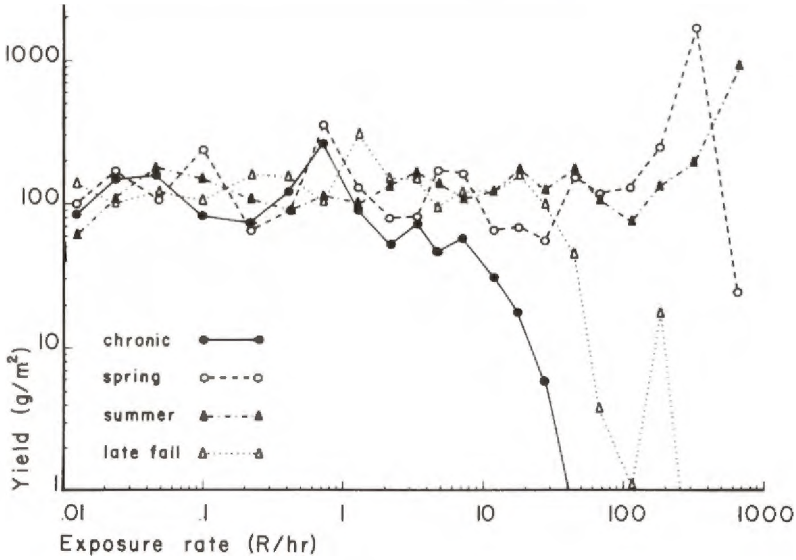

FIGURE 13. Total vegetation biomass of a shortgrass plains community in north-central Colorado in response to chronic (•) and 30 day seasonal γ exposures: (O) spring, (▲) summer, and (△) late fall. (After Fraley, L., Jr., Ph. D. dissertation, Colorado State University, Fort Collins, 1971.)

izing radiation exposure after some threshold exposure is exceeded. In some instances, total productivity may increase within certain exposure ranges in response to release from competition or an altered environment. It is not surprising to find cases where indexes of community structure are more responsive to radiation stress than indexes of total community productivity. It should be realized of course, that although total net primary production determines the total energy potentially harvestable by consumer organisms, the actual harvest, as well as the species engaged in such harvest, is very much dependent upon which plant species are involved in primary production.

Several other types of radiation effects on plant populations have been investigated, including changes in reproductive potential, morphological abnormalities, and interactions with other stresses and with attributes of the plants themselves. For example, additional studies in the oak-pine forest include the effects of ionizing radiation in megasporogenesis[201] and seed germination and seedling growth.[202] Mergen and Stairs[203] reported on the effects of chronic gamma irradiation on physiological and genetic aspects of sexual reproduction.

Radiation-induced anomalies in the secondary xylem of short-leaf pine *(Pinus echinata)* growing in the vicinity of the Georgia air-shielded reactor were observed by Clark and Hamilton[204] and gross anatomical and histological effects in irradiated white oak *(Quercus alba)* and black oak *(Q. velutina)* trees were observed by Mericle et al.[205] Witherspoon and Taylor[206] also reported anatomical modifications in several tree species growing contiguous to the Oak Ridge National Laboratory's unshielded fast-neutron reactor.

The natural environment poses many forms of stress which may alter significantly the response of plants and animals to ionizing radiation.[207] This fact reduces considerably our ability to repredict with precision radiation effects on populations and communities. In addition, attributes of individual organisms can considerably modify their response to applied radiation stress or radioactive contamination. For example, the location and protection of meristematic tissues in buds and root tips, which are critical tissues in terms of radiation damage, determine in large measure the effectiveness of a

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Table 10
ESTIMATED SHORT-TERM* RADIATION EXPOSURES REQUIRED TO DAMAGE VARIOUS PLANT COMMUNITIES[17,208,214,215]

Community type	Exposures in kR to produce		
	Minor effects	Intermediate effects	Severe effects
Coniferous forest	0.1—1	1—2	>2
Deciduous forest	1—10	5—35	>10
Shrub	1—5	5—20	>20
Tropical rain forest	4—10	10—40	>40
Rock outcrop (herbaceous)	8—10	10—40	>40
Old-fields (herbaceous)	3—10	10—100	>100
Herbaceous forest understory	20—40	40—60	>60
Grassland	8—10	10—100	>100
Herbaceous invaders	40—60	60—160	>160
Moss-lichen	10—100	50—500	>200

* Short-term exposures range from about 8 to 30 days according to the literature from which this table was derived. Exposures might be reduced by factors of 2 to 4 for acute or fallout-decay irradiation. Chronic daily exposures required to produce comparable effects required may be estimated roughly as 1 to 4 % of the exposures tabulated above.

given dose or contamination level.[17] Factors such as age and structure,[208] physiological state[191,200] and, as is well known, nuclear and chromosome variables,[209] play an important role in determining the radiosensitivity of individuals and, hence, of populations and communities.

Populations and communities have the capability to recover from radiation damage provided that such damage is not complete or total. Mechanisms which operate within cells and tissues are ultimately involved with recovery of damaged individuals. Replacement of damaged or dead individuals with new individuals from healthy propagules can occur; particularly if the damaged area is near or adjacent to a similar but undamaged area. Although rather extensive time periods may be involved, communities may recover by the process of succession. Let us consider a few studies in which recovery has been observed following radiation damage. One should bear in mind that most radiation studies in natural plant communities involve relatively short time periods. Further, relatively small areas of severe damage have been observed with surrounding undamaged areas able to provide a source of seed, spores, rhizomes, or other propagules. Further, in general, soils in the radiation-damaged areas were reasonably well developed at the onset of the studies described. Generally, observations which have been made on recovery from damage resulting from ionizing radiation have occurred under conditions relatively favorable to rapid succession. Succession could be slowed greatly if a huge land area were to be severely denuded[210] or if denudation were to persist for a long enough period of time to allow soil deterioration.

Daniel[188] observed successional patterns in old-field communities which were exposed to neutron-gamma irradiation from an air-shielded reactor in Georgia. Loblolly pine *(Pinus taeda)* and river birch *(Betula nigra)* which were beginning to invade the field were killed by radiation and the community became relatively static. Considerable regeneration from underground parts was observed in greenbrier *(Smilax)* even though aerial parts were killed.[211] The major form of recovery of hardwood stands exposed to the same radiation was also by sprouting from protected underground tissues.[212]

Miller[191] found that initial changes in old-fields following short-term exposures

largely involved replacement of perennial species by annual herbs. He suggested that the particular species involved in succession following irradiation are highly dependent upon the season in which irradiation takes place and that "...radiation administered in this seasonal form is not too different from other environmental factors with respect to succeeding recovery generations of plant populations." Shortgrass plains vegetation which had been killed or severely damaged by short-term irradiation was rapidly replaced by vigorous stands of invader species within a year following irradiation.[184] Revegetation rates varied, depending upon season of exposure, with revegetation being slowest in plots irradiated in the dormant condition in late fall.

Jordan[213] studied recovery of irradiated rain forest vegetation and compared such recovery to that following mechanical stripping and herbicide treatment. Recovery following radiation stress was generally similar to recovery from the other forms of stress, with a major difference being a marked tendency for sprouting from shielded bases of irradiated trees. Odum,[192] in his summary of this rain forest study, states:*

"...the zone between killing-removal and undetectable life-as-usual was very narrow in time and space... These observations are evidence of rapid selective replacement and repair which operate in a complex system... The greater stability of natural systems may be due to their ability to clean out error or cover it up and restore some new functions rapidly, a property that may be best developed in the tropical forest... The results at El Verde in some slight measure may speak for greater resilience of the tropical world to acute radiation catastrophe..."

Based on numerous individual investigations, the comparative radiosensitivity of different plant communities can be examined. Several investigators have made estimates of radiation doses which would be required to cause minor, intermediate, and severe effects on several types of North American plant communities.[17,208,214,215] Table 10 presents estimates of short-term (8 to 30 day) exposures required to produce minor, intermediate, and severe effects on some major plant communities. Minor effects are considered to include temporary changes in productivity, reproduction, and phenology. Recovery from such effects would occur rapidly following radiation stress. Intermediate effects are considered to include changes in species composition and diversity through selective mortality of the more radiosensitive community components. Recovery from such effects may take place through the processes of plant succession and may require from one to several generations. Severe effects are considered as those which drastically change species composition, or which may cause mortality of all or nearly all higher plants. Recovery may be very slow (decades) following severe effects, or it may be delayed for very long periods (centuries) if the soil becomes subject to leaching of nutrients or erosion.

b. Animal Populations

In general, knowledge of radiation effects on animal populations in irradiated ecosystems is more limited than on plant populations and communities. This stems largely from difficulties inherent in studying wild, free-ranging animals in a quantitative manner. Nevertheless, several pertinent studies have been conducted on animal populations in irradiated ecosystems (Tables 3 and 4). Generally, these studies deal with effects on reproduction, mortality, growth or fitness, and behavior. A definitive review of the effects of chronic radiation on animal populations was prepared by Turner.[18]

In the chronically irradiated oak-pine forest at Brookhaven National Laboratory

* From Odum, H. T., Summary: an emerging view of the ecological system at El Verde, in A Tropical Rain Forest: A Study of Irradiation and Ecology at El Verde, Puerto Rico, U.S. AEC Rep. TID-24270 (PRNC-138), Odum, H. T. and Pigeon, R. F., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1970, I191.

various observations have been made that suggest both direct and indirect effects of radiation. Although species diversity and number of breeding pairs of birds are rather low in this oak-pine forest, Wagner and Marples[216] studied the breeding success of passerine birds approximately four years after initiation of chronic irradiation. Their observations on nests of five species disclosed the lack of embryos in eggs located in areas receiving 21, 39, and 130 R/day. Bongiorno and Pearson[217] studied the white-footed mouse *(Peromyscus leucopus)* in the irradiated oak-pine forest but were unable to attribute any effects to ionizing radiation. The mouse population studied, in large part, was exposed to less than 3 R/day. Woodwell and Brower[218] observed a population explosion of aphids *(Myzocallis discolor)* on some white oaks damaged by radiation. The population increase was correlated with a change in a predator population as well as sugar, total N, and lipid content of white oak leaves. Aphids were not observed in the undamaged forest. A colony of ants, *Formica integra*, in the same study area constructed a covered runway 12.5 m long which was used exclusively for travel from the nest.[219] The tunnel was oriented away from the radiation source, suggesting a behavioral response to the radiation field.

Significant studies of chronically-irradiated animal populations have been conducted within large enclosures in Rock Valley at the Nevada Test Site in southern Nevada.[18] Turner and his associates conducted investigations on populations of lizards confined to irradiated and control enclosures. After 5 years of chronic irradiation at about 2 rad/day, no significant differences in sex ratios or age distributions were observed between the irradiated and control populations of the iguanid lizard *(Uta stansburiana)*, nor was there a significant difference between maximal life spans.[220] A study of genetic variation in the populations disclosed no significant difference between the irradiated and control populations in the relative allele frequencies for 19 loci which control selected proteins.[221] It was observed that some female lizards became sterile after accumulating a radiation dose of about 500 rad while others did not become sterile until accumulation of 1000 rad or more. Further, it was observed that some females displayed half sterility (one functional ovary).[222] Radiation-induced sterility in the leopard lizard *(Crotaphytus wislizenii)* and whiptailed lizard *(Cnemidophorus tigris)* was also investigated.[223] Mean annual tissue doses, estimated with lithium fluoride microdosimeters, were 400 to 500 rad for leopard lizards and about half of this amount for the whiptailed lizards. Sterility was observed in both species and attributed to "long-term" gamma radiation exposure. *U. stansburiana* occupying the same irradiated enclosure, apparently displayed normal reproduction which, when contrasted with the leopard and whiptailed lizard, was "...attributed to their markedly different lifespans and demographic regimes." Summarizing findings on the effects of radiation on lizard populations, Turner[18] comments:*

> "The responses of the lizards to continuous irradiation are an excellent illustration of how the demographic properties of natural populations mediate the effects of chronic stresses. The most simple reaction to the irradiation has been that of leopard and horned lizards [*Phrynosoma platyrhinos*]. All the mature females became sterile; reproduction was blocked, and these populations are now nearly extinct. Although the same sort of sterility has occurred in female whiptails and utas, these irradiated populations are still extant and the density of *Uta* in 1972 was apparently normal. Does this mean the ovaries of the leopard and horned lizards are more sensitive to chronic irradiation than those of the persisting species? This question has not been explored, but there is a more likely explanation which should be considered first... Probably the most important species attributes yet to be considered are those related to life history: individual life spans, time of sexual maturity, and population age distributions."

The Rock Valley facility was initially established by French to study the effects of

* From Turner, F. B., *Adv. Radiat. Biol.*, 5, 83, 1975. With permission.

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relatively low-level chronic irradiation on small rodent populations.[224] Turner[18] summarizes the history of the project, its design and the research efforts of French and his associates. Although a few other rodent species were investigated, the pocket mouse *(Perognathus formosus)* population was emphasized in these studies. These studies indicated an alteration in normal survivorship of pocket mice receiving chronic exposures of about 1 R/day as compared to controls.[63] Survival was depressed in irradiated mice during the first 6 months of life, however those surviving the first 6 months showed increased survival relative to the controls over the next 3 years. Age specific fertility was studied in this population, with indication of a slightly reduced intrinsic rate of natural increase for the irradiated animals. However, this effect was not conclusive. Furthermore, pocket mice in the irradiated enclosures generally maintained higher population densities than those in the control enclosures.

Although the air-shielded reactor in Dawsonville, Ga. was not established for the purpose of ecological investigations, a number of meaningful studies were conducted there. In addition to observations on the effects of the mixed gamma-neutron flux on vegetation, observations were made on birds and cotton rats released in the area. Schnell[225] released cotton rats prior to operations at the reactor site and following neutron-gamma irradiation he observed lack of aggressiveness and alertness, impairment of motor reflexes and equilibrium, and general reduction in activity. Schnell also observed that ionizing radiation adversely affected territorial birds.[226] He was unable to demonstrate effects on nonsinging individuals, as their numbers declined slightly on both irradiated and control areas.

Cadwell[227] investigated colony formation of the western harvester ant *(Pogonomyrmex occidentalis)* in the vicinity of the shortgrass prairie gamma radiation source in Colorado. Although the exposure rate at the nest site was 18 R/hr he did not notice any habitat modification that would indicate an avoidance response to ionizing radiation. In fact, subsequent studies by Cadwell[228] indicated that this ant utilized an area totally denuded of higher vegetation by radiation to a greater extent than vegetated areas. The reason for this is not totally clear, but possibly the ants preferred to establish pathways in the denuded area for the sake of foraging efficiency. Another ant, *Myrmica sabuleti americana*, responded indirectly to the radiation field by exhibiting activity only in the areas where grass species were not severely damaged by radiation. This animal apparently tends grass root aphids and is thus closely associated with the vegetation pattern.

Investigations of animals in the irradiation field of the tropical rain forest in Puerto Rico included invertebrates, lizards, frogs, birds and a mammal. Over the period of the investigation, radiation had no apparent effect on the microarthropod fauna of the soil and litter.[198,229] However, there was increased leaf-fall in the immediate vicinity of the radiation source, which may have caused subsequent changes in the litter microarthropod populations. Observations on nest condition, tunnel occupancy, and behavior of termites in the irradiation field disclosed nest deterioration at cumulative exposures of 1000 R and higher, decrease of carbon dioxide emission from irradiated nests, and abandonment of nests within 3 m of the radiation source.[230] Initially, the rain forest had few mosquitoes, but following irradiation *Aedes aegypti* increased in numbers and an epizootic virus disease occurred in the rodent population, suggesting that radiation played a part in its initiation.[231] The snail, *Caracolus caracolla*, received smaller radiation doses than expected as it spent a portion of its existence under rocks. Using microdosimeters attached to the animal, however, it was observed that some individuals nevertheless received exposures of 29 kR in 92 days (315 R/day) and still survived.[232] Observing the tree frog, *Eleutherodactylus portoricensis*, and two species of lizards *(Anolis gundlachi* and *A. evermanni)* in the irradiated rain forest, Turner and Gist[233] reported that animals were killed and that density of all species was reduced

within 15 to 20 m of the source. Young individuals displayed better survival than adults, perhaps because they spent more time underground. Recher[234] observed fewer avian territories close to the source following irradiation, and Weinbren and colleagues[235] reported no significant effect on roof rat *(Rattus rattus)* populations.

Small mammal and bird populations in the Enterprise, Wisconsin radiation field were studied by Buech.[236-237] Six different mammal genera and seven species, totalling 67 individuals, were captured and dosimeters were attached to each animal. The maximum exposure rate was 1 to 2 R/day. No effect of radiation on mammalian survival was observed. Considering the small number of avian nests observed, the results were not definitive. The investigator did comment however, that for the three nests within the exposure rate range of 39 to 128 R/day, there was an indication that a total exposure of 400 to 500 R during incubation is "...likely to increase hatching failures or result in subsequent lethal effects during the nestling stage."

Although not falling strictly within this category or others discussed in this chapter, the study by Bonham and Donaldson[238] is of considerable interest. Chinook salmon embryos were exposed to irradiation from a ^{60}Co source during embryonic development. An exposure rate of 0.5 R/day was delivered from shortly after egg fertilization until feeding commenced, yielding a total exposure of 33 to 40 R. In succeeding years, greater doses were given. Following rearing, fingerlings were marked and released and records kept of fish returning from the ocean to the hatchery. The authors stated the results of early experiments as follows:*

"Total number of returning spawners and egg production per female from the irradiated groups usually exceeded those of the controls. At 2.5 times the previous radiation level or 1.3 r/day, the survival, growth, and occurrence of abnormalities in juveniles showed no significant difference between controls and experimentals."

C. Summary Comments on Chronic Irradiation Studies

The following summary comments on chronic irradiation response of populations and communities are paraphrased largely from the previously cited reviews by Whicker and Fraley[17] on terrestrial plant communities, Turner[18] on terrestrial animal populations, and Blaylock and Trabalka[19] on aquatic organisms.

Concerning plant communities, stands characteristic of harsh environments and climatic extremes are relatively radioresistant and early seral stage communities tend to be more resistant than following successional stages. Radiosensitivity of plants is related to characteristics of chromosomes and cell populations and to stature and growth form, with the smaller herbaceous plants being more radioresistant than larger, woody species. Vascular species are much more sensitive than thallophytes. Reproduction and productivity may be reduced at reasonably low exposures. At higher exposures, breakdown of community structure can be expected. Alteration of the plant community is related to radiation dose rate, time of exposures, radiosensitivity of component populations and to secondary effects and interactions.

With respect to performance of terrestrial animal populations, the process most susceptible to impairment by radiation stress is reproduction. However, some populations that exhibit rapid repopulation potential can often adjust to reduced natality and still maintain stable numbers. On the other hand, longer-lived species with normally low reproductive potential can gradually decline in density to the point of extinction at relatively low chronic exposure rates. Across the animal kingdom, there is a 2 to 3 order-of-magnitude range in innate sensitivity to radiation. Furthermore, the biotic

* From Bonham, K. and Donaldson, L. R., Low-level chronic irradiation of salmon eggs and alevins, in Disposal of Radioactive Wastes into Seas, Oceans and Surface Waters, Publ. No. STI/PUB/126, International Atomic Energy Agency, Vienna, 1966, 869.

and abiotic environment, as well as many other innate characteristics can significantly alter the response of animal populations to radiation. As a result, the prediction of population response in irradiated ecosystems becomes a very difficult task, unless the exposures are either very low, or very high.

Studies on natural aquatic populations have been limited to systems that have been contaminated with radionuclides to produce dose rates generally less than 1 rad/day. At such levels, the responses of aquatic populations have been very difficult to document and quantify. While genetic mutations have been observed at the chromosome level in organisms subject to such dose levels, the effects on fecund populations subject to strong selective pressures appear inconsequential. Based on laboratory investigations, developing embryos of fish can be expected to be one of the most sensitive components of aquatic systems to radiation, but there is considerable variation between species, as well as within species, depending on stage of development and environmental factors.

REFERENCES

1. **Bacq, Z. M. and Alexander, P.**, *Fundamentals of Radiobiology*, 2nd ed., Pergamon Press, Elmsford, N.Y., 1961.
2. **Casarett, A. P.**, *Radiation Biology*, Prentice-Hall, Englewood Cliffs, N.J., 1968.
3. **Arena, V.**, *Ionizing Radiation and Life*, C. V. Mosby, St. Louis, 1971.
4. Advisory Committee on the Biological Effects of Ionizing Radiations, The Effects on Populations of Exposure to Low Levels of Ionizing Radiation, National Academy of Sciences-National Research Council, Washington, D.C., 1972.
5. Scientific Committee on the Effects of Atomic Radiation, Ionizing radiation: Levels and Effects, Vol. 2, United Nations, New York, 1972; *Nucl. Sci. Abstr.*, 27(7), 15040
6. **Pierce, C. M.**, The Effects of Radiation and Radioisotopes on the Life Processes. An Annotated Bibliography, Book 1 and 2. U.S. AEC Rep. TID-3098, U.S. Atomic Energy Commission, Washington, D.C., 1963.
7. **Ingram, M.**, Biological Effects of Ionizing Radiation. An Annotated Bibliography Covering the Years 1898-1957, U.S. AEC Rep. TID-3097, U.S. Atomic Energy Commission, Washington, D.C., 1966.
8. **Bost, W. E., Ward, H. L., and Voress, H. E.**, Combined Subject and Author Indexes to Radiobiology Bibliographies, U.S. AEC Rep. TID-3097, U.S. Atomic Energy Commission, Washington, D.C., 1967.

8a. **Bost, W. E., Ward, H. L., and Voress, H. E.**, Biological Effects of Ionizing Radiation, U.S. AEC Rep. TID-3098, U.S. Atomic Energy Commission, Washington, D.C., 1967.

8b. **Bost, W. E., Ward, H. L., and Voress, H. E.**, The Effects of Radiation and Radioisotopes on the Life Processes, U.S. AEC Rep. TID-3099, U.S. Atomic Energy Commission, Washington, D.C., 1967.

9. **Anon.**, Low-Level Radiation: Biological Interactions, Risks, and Benefits. A Bibliography, U.S. DOE Rep. TID-3373, U.S. Department of Energy, Washington, D.C., 1978.
10. **Wichterman, R.**, Biological effects of ionizing radiations on protozoa: some discoveries and unsolved problems, *BioScience*, 22(5), 281, 1972.
11. **Metalli, P. and Ballardin, E.**, Radiobiology of *Artemia*: radiation effects and ploidy, *Curr. Top. Radiat. Res. Q.*, 7(1970-72), 181, 1972.
12. **O'Brien, R. D. and Wolfe, L. S.**, Nongenetic effects of radiation, in *Radiation, Radioactivity, and Insects*, Academic Press, New York, 1964, 23.
13. **Brunst, V. V.**, Effects of ionizing radiation on the development of amphibians, *Q. Rev. Biol.*, 40(1), 1, 1965.
14. **Cosgrove, G. E.**, Reptilian radiobiology, *J. Am. Vet. Med. Assoc.*, 159(11), 1678, 1971.
15. **Mellinger, P. J. and Schultz, V.**, Ionizing radiation and wild birds: a review, *Crit. Rev. Environ. Control*, 5(3), 397, 1975.
16. **Sparrow, A. H., Binnington, J. P., and Pond, V.**, Bibliography on the Effects of Ionizing Radiations on Plants, 1896-1955, U.S. AEC Rep. BNL-504(L-103) Brookhaven National Laboratory, Upton, Long Island, N.Y., 1958.

17. **Whicker, F. W. and Fraley, L., Jr.**, Effects of ionizing radiation on terrestrial plant communities, *Adv. Radiat. Biol.*, 4, 317, 1974.
18. **Turner, F. B.**, Effects of continuous irradiation on animal populations, *Adv. Radiat. Biol.*, 5, 83, 1975.
19. **Blaylock, B. G. and Trabalka, J. R.**, Evaluating the effects of ionizing radiation on aquatic organisms, *Adv. Radiat. Biol.*, 7, 103, 1978.
20. **Chipman, W. A.**, Ionizing radiation, in *Marine Ecology*, Vol. 1, (Part 3), Kinne, O., Ed., John Wiley & Sons, New York, 1972, 1579.
21. **Seymour, A. H. et al.**, Aquatic environment, in *Long-Term Worldwide Effects of Nuclear-Weapons Detonations*, National Research Council, National Academy of Sciences, Washington, D.C., 1975, 103.
22. **Templeton, W. L.**, Effects of radiation on aquatic populations, in *Environmental Toxicity of Aquatic Radionuclides: Models and Mechanisms*, Miller, M. W. and Stannard, J. N., Eds., Ann Arbor Science, Mich., 1976, 287.
23. **Templeton, W. L., Nakatani, R. E., and Held, E. E.**, Radiation effects, in *Radioactivity in the Marine Environment*, Panel on Radioactivity in the Marine Environment, National Academy of Sciences, Washington, D.C., 1971, 223.
24. **Templeton, W. L. et al.**, Effects of ionizing radiation on aquatic populations and ecosystems, in Effects of Ionizing Radiation on Aquatic Organisms and Ecosystems, Tech. Rep. Ser. No. 172, International Atomic Energy Agency, Vienna, 1976, 87.
25. **Andrushaitis, G. P., Ed.**, *Radioecology of Water Organisms* (in Russian), Vol. 3, Zinatne, Riga, 1973; AEC-tr-7529 (English transl.), U.S. Atomic Energy Commission, Washington, D.C., 1974.
26. **Polikarpov, G. G.**, Part III. The effect of nuclear radiation on marine organisms, in *Radioecology of Aquatic Organisms (English transl.)*, Schultz, V. and Klement, A. W., Jr., Eds., North-Holland, Amsterdam, 1966, 183.
27. **Polikarpov, G. G.**, Effects of ionizing radiation upon aquatic organisms (chronic irradiation), in *Atti della Giornata Sul Tema Alcuni Aspetti di Radioecologia*, 20th Congr. Natl., Associazione Italiana di Fisica Sanitaria e Protezione Contro le Radiazioni, Bologna, 1977, 25.
28. **Sorokin, B. P., Ed.**, Effect of ionizing radiation on the organism. The problem of the effect of radioactive water pollution on the reproduction of commercial fishes (in Russian), *Tr. Polyarn. Nauchno-Issled. Proektn. Inst. Morsk. Rybn. Khoz. Okeanogr.*, 29, 1, 1971; AEC-tr-7418 (English transl.), U.S. Atomic Energy Commission, Washington, D.C., 1973.
29. **Neel, J. V.**, *Changing Perspectives on the Genetic Effects of Radiation*, Charles C Thomas, Springfield, Ill., 1963.
30. **Asimov, I. and Dobzhansky, T.**, The genetic effects of radiation, Understanding the Atom Series, U.S. Atomic Energy Commission, Washington, D.C., 1968.
31. **Dubinin, N. P., Shevchenko, V. A., and Pomerantseva, M. D.**, Effect of ionizing radiation on populations (radiation-genetic aspects) (in Russian), in *Contemporary Problems of Radiobiology*, Vol. 2, Klechovskiy, V. M., Polikarpov, G. G., and Aleksakhim, R. M., Eds., Atomizdat, Moscow, 1971, 183; *Radioecology* (English transl.), Greenberg, D., Ed., John Wiley & Sons, New York, 1973, 157.
32. **Green, E. L.**, Genetic effects of radiation on mammalian populations, *Annu. Rev. Genet.*, 2, 87, 1968.
33. **Van Cleave, C. D.**, Late Somatic Effects of Ionizing Radiation, U.S. AEC Rep. TID-24310, U.S. Atomic Energy Commission, Washington, D.C., 1968.
34. **Thomson, J. R.**, *Radiation Protection in Mammals*, Reinhold, New York, 1962.
35. **Bond, V. P., Fliedner, T. M., and Archambeau, J. O.**, *Mammalian Radiation Lethality: A Disturbance in Cellular Kinetics*, Academic Press, New York, 1965.
36. **Carlson, W. D. and Gassner, F. X., Eds.**, *Effects of Ionizing Radiation on the Reproductive System*, Pergamon Press, Elmsford, N.Y., 1964.
37. **Taliaferro, W. H., Taliaferro, L. G., and Jaroslow, B. N.**, *Radiation and Immune Mechanisms*, Academic Press, New York, 1964.
38. **Kimeldorf, D. J. and Hunt, E. L.**, *Ionizing Radiation: Neural Function and Behavior*, Academic Press, New York, 1965.
39. **Walburg, H. E., Jr.**, Radiation-induced life-shortening and premature aging, *Adv. Radiat. Biol.*, 5, 145, 1975.
40. **Sikov, M. R. and Mahlum, D. D., Eds.**, Radiation Biology of the Fetal and Juvenile Mammal, (AEC Symp. Ser. 17), U.S. AEC Rep. CONF-690501, U.S. Atomic Energy Commission, Washington, D.C., 1969.
41. **IAEA**, Effects of Ionizing Radiation on Seeds, Publ. STI/PUB/13, International Atomic Energy Agency, Vienna, 1961.
42. **Bond, V. P. and Sugahara, T., Eds.**, *Comparative Cellular and Species Radiosensitivity*, Williams & Wilkins, Baltimore, Md., 1969.

43. **Various authors,** Fundamental Aspects of Radiosensitivity (Brookhaven Symp. Biol. 14), U.S. AEC Rep. BNL-675(C-31), Brookhaven National Laboratory, Upton, Long Island, N.Y., 1961.
44. **Upton, A. E.,** *Radiation Injury: Effects, Principles, and Perspectives,* University of Chicago Press, Ill., 1969.
45. **Drew, R. T. and Eisenbud, M.,** The pulmonary dose from ^{220}Rn received by indigenous rodents of the Morro Do Ferro, Brazil, *Radiat. Res.,* 42(2), 270, 1970.
46. **Gruneberg, H., Bains, G. S., Berry, R. J., Riles, L., Smith, C. A. B., and Weiss, R. A.,** A search for genetic effects of high natural radioactivity in South India, *Med. Res. Counc. (London) Spec. Rep. Ser. SRS,* 307, 1966.
47. **Verkhovskaya, I. N., Ed.,** *Radioecological Studies in Natural Biogeocenoses* (in Russian), Nauka, Moscow, 1972; *Nucl. Sci. Abstr.,* 26(23), 56134.
48. **Cullen, T. L. and Penna Franca, E., Eds.,** *Int. Symp. Areas of High Natural Radioactivity,* Moscow Academia Brazileira de Ciencias, Rio de Janeiro, Brazil, 1977; *ERDA Energy Res. Abstr.,* 2(16), 40196.
49. **Sigler, W. F., Helm, W. T., Angelovic, J. W., Linn, D. W., and Martin, S. S.,** The effects of uranium mill wastes on stream biota, *Utah Agric. Exp. Stn. Bull.,* 462, 1966.
50. **Krumholz, L. A.,** Observations on the fish population of a lake contaminated by radioactive wastes, *Bull. Am. Mus. Nat. Hist.,* 110(art. 4), 277, 1956.
51. **Dunaway, P. B. and Kaye, S. V.,** Effects of ionizing radiation on mammal populations on the White Oak Lake bed, in *Radioecology,* Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 333.
52. **Blaylock, B. G.,** Chromosomal polymorphism in irradiated natural populations of *Chironomous, Genetics,* 53(1), 131, 1966.
53. **Blaylock, B. G.,** The fecundity of a *Gambusia affinis affinis* population exposed to chronic environmental radiation, *Radiat. Res.,* 37(1), 108, 1969.
54. **Rhoads, W. A. and Platt R. B.,** Beta radiation damage to vegetation from close-in fallout from two nuclear detonations, *BioScience,* 21(22), 1121, 1971.
55. **Koranda, J. J. and Martin, J. R.,** Persistence of radionuclides at sites of nuclear detonations, in Biological Implications of the Nuclear Age *(AEC Symp. Ser. 16),* U.S. AEC Rep. CONF-690303, Goulden, A. M., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1969, 159.
56. **Turner, F. B. and Gist, C. S.,** Influences of a thermonuclear cratering test on close-in populations of lizards, *Ecology,* 46(6), 845, 1965.
57. **Stone, W. S., Sheeler, M. R., and Wilson, F. D.,** Genetic studies of irradiated natural populations of Drosophila. V. Summary and discussion of tests of populations collected in the Pacific Proving Ground from 1955 through 1959, in *Studies in Genetics II. Research Reports on Drosophila Genetics, Taxonomy and Evolution,* Publ. 6205, Wheeler, M. R., Ed., University of Texas, Austin, 1962, 1.
58. **Gorbman, A. and James, M. S.,** An exploratory study of radiation damage in the thyroids of coral reef fishes from the Eniwetok Atoll, in *Radioecology,* Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 385.
59. **DiGregorio, D., Dunaway, P. B., Story, J. D., and Kitchings, J. T., III,** Cesium-137 accumulation, dosimetry, and radiation effects in cotton rats, in Survival of Food Crops and Livestock in the Event of Nuclear War *(AEC Symp. Ser. 24),* U.S. AEC Rep. CONF-700909, Benson, D. W. and Sparrow, A. H., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1971, 535.
60. **Murphy, P. G. and McCormick, J. F.,** Ecological effects of acute beta irradiation from simulated-fallout particles on a natural plant community in Survival of Food Crops and Livestock in the Event of Nuclear War, *(AEC Symp. Ser. 24),* U.S. AEC Rep. CONF-700909, Bensen, D. W. and Sparrow, A. H., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1971, 454.
61. **Peredel'skii, A. A.,** Ecological study of ionizing radiation, USSR, *Achievements in Science; Biology,* No. 1, Radiobiology, 1959, 379; English transl., (JPRS: 859-D; OTS: 59-11; page 758).
62. **Platt, R. B., McGinnis, J. T., and Cowan, J. J.,** An automatically controlled gamma irradiation facility at Emory University, *Bull. Ga. Acad. Sci.,* 22(3/4), 75, 1964.
63. **French, N. R., Maza, B. G., Hill, H. O., Aschwanden, A. P., and Kaaz, H. W.,** A population study of irradiated desert rodents, *Ecol. Monogr.,* 44(1), 45, 1974.
64. **Polikarpov, G. G.,** Experimental methods for radiobiological investigations with developing fish eggs, in Methodology for Assessing Impacts of Radioactivity on Aquatic Ecosystems, Tech. Rep. Ser. No. 190, International Atomic Energy Agency, Vienna, 1979, 173.
65. **Woodhead, D. S.,** Levels of radioactivity in the marine environment and the dose commitment to marine organisms, in Radioactive Contamination of the Marine Environment, Publ. STI/PUB/313, International Atomic Energy Agency, Vienna, 1973, 499.
66. **Woodhead, D. S.,** The radiation dose received by plaice *(Pleuronectes platessa)* from the waste discharged into the north-east Irish Sea from the fuel reprocessing plant at Windscale, *Health Phys.,* 25(2), 115, 1973.

BEST AVAILABLE COPY

67. **Blaylock, B. G. et al.,** Applied aquatic studies. Radionclides in the sediments of White Oak Creek and White Oak Lake, in Environmental Sciences Division Annual Progr. Rep. Period Ending September 30, 1972, U.S. AEC Rep. ORNL-4848, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1972, 79.
68. **Trabalka, J. R. and Allen, C. P.,** Aspects of fitness of a mosquito fish *Gambusia affinis* population exposed to chronic low-level environmental radiation, *Radiat. Res.*, 70(1), 198, 1977.
69. **Kaye, S. V.,** Use of miniature glass rod dosimeters in radiation ecology, *Ecology*, 46(1/2), 201, 1965.
70. **French, N. R.,** Radiation sensitivity of rodent species, *Nature (London)*, 222(5197), 1003, 1969.
71. **Watson, D. G. and Templeton, W. L.,** Thermoluminescent dosimetry of aquatic organisms, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1125.
72. **White, J. C., Jr. and Angelovic, J. W.,** Tolerances of several marine species to Co 60 irradiation, *Chesapeake Sci.*, 7(1), 36, 1966.
73. **Willard, W. K.,** Dynamics of *Conotrachelus nenuphar* (Coleoptera: Curculioninae) populations following exposure to ionizing radiation, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1144.
74. **Howden, H. F. and Auerbach, S. I.,** Some effects of gamma radiation on *Trogoderma sternale* Jayne, *Ann. Entomol. Soc. Am.*, 51(1), 48, 1958.
75. **Willard, W. K. and Cherry, D. S.,** Comparative radiosensitivity in the Class Insecta, *J. Theor. Biol.*, 52(1), 149, 1975.
76. **Blaylock, B. G.,** Effects of ionizing radiation on interspecific competition, in Symposium on Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1969, 61.
77. **Erdman, H. E.,** X-radiation and temperature modification of reproductive performance of single-species and mixed-species cultures of *Tribolium confusum* and *T. castaneum*, *Physiol. Zool.*, 39(2), 160, 1966.
78. **Edwards, C. A.,** Effects of gamma irradiation on populations of soil invertebrates, in Symposium on Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1969, 68.
79. **Engel, D. W. and Davis, E. M.,** The effects of gamma radiation on the survival and growth of brine shrimp, *Artemia salina*, in *Radioecology and Energy Resources*, Cushing, C. F., Jr. et al., Eds., Dowden, Hutchinson & Ross, Stroudsburg, Pa., 1976, 376.
80. **Holton, R. L., Osterberg, C. L., and Forster, W. O.,** Effect of gamma irradiation on the maintenance of population size in the brine shrimp *Artemia*, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1198.
81. **Angelovic, J. W. and Engel, D. W.,** Interaction of gamma irradiation and salinity on respiration of brine shrimp *(Artemia salina)* nauplii, *Radiat. Res.*, 35(1), 102, 1968.
82. **Engel, D. W., Davis, E. M., Angelovic, J. W., and Smith, D. E.,** Effect of radiation, salinity, and temperature on the ionic regulation of the blue crab, *Callinectes sapidus*, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1113.
83. **Welander, A. D.,** Some effects of X-irradiation of different embryonic stages of the trout *(Salmo gairdnerii)*, *Growth*, 18(4), 227, 1954.
84. **Foster, R. F., Donaldson, L. R., Welander, A. D., Bonham, K., and Seymour, A. H.,** The effect on embryos and young of rainbow trout from exposing the parent fish to X-rays, *Growth*, 13(2), 119, 1949.
85. **Angelovic, J. W., White, J. C., Jr., and Davis, B. M.,** Interactions of ionizing radiation, salinity, and temperature on the estuarine fish, *Fundulus heteroclitus*, in Symposium on Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1969, 131.
86. **Edmundson, E. H., Jr.,** Effects of gamma radiation and temperature on growth of juvenile rainbow trout *(Salmo gairdneri)*, *Northwest Sci.*, 50(3), 183, 1976.
87. **Ulrikson, G. U.,** Radiation effects on serum proteins, hematocrits, electrophoretic patterns and protein components in the bluegill *(Lepomis macrochirus)* in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1100.
88. **Holzberg, S. and Schroder, J. H.,** Behavioural mutagenesis in the convict cichlid fish, *Cichlasoma nigrofasciatum* Guenther. I. The reduction of male aggressiveness in the first post-irradiation generation, *Mutat. Res.*, 16(3), 289, 1972.
89. **Sparrow, A. H., Nauman, C. H., Donnelly, G. M., Willis, D. L., and Baker, D. G.,** Radiosensitivities of selected amphibians in relation to their nuclear and chromosome volumes, *Radiat. Res.*, 42(2), 353, 1970.

90. **Conger, A. D. and Clinton, J. H.,** Nuclear volumes, DNA contents, and radiosensitivity in whole-body-irradiated amphibians, *Radiat. Res.*, 54(1), 69, 1973.
91. **Landreth, H. F., Dunaway, P. B., and Cosgrove, G. E.,** Effects of whole-body gamma irradiation on various life stages of the toad, *Bufo woodhousei* Fowleri, *Radiat. Res.*, 58(3), 432, 1974.
92. **Tinkle, D. W.,** Effects of radiation on the natality, density and breeding structure of a natural population of lizards, *Uta stansburiana*, *Health Phys.*, 11(12), 1595, 1965.
93. **Norris, R. A.,** Some effects of X-irradiation on the breeding biology of eastern bluebirds, *Auk*, 75(4), 444, 1958.
94. **Lofts, B., Marshall, A. J., and Rotblat, J.,** Effects of whole-body irradiation on the breeding plumage of the weaver finch, *Quelea quelea*, *Nature (London)*, 187(4737), 615, 1960.
95. **Lofts, B. and Rotblat, J.,** The effects of whole-body irradiation on the reproductive rhythm of the avian testis, *Int. J. Radiat. Biol.*, 4(3), 217, 1962.
96. **Willard, W. K.,** Relative sensitivity of nestlings of wild passerine birds to gamma radiation, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 345.
97. **Garg, S. P., Zajanc, A., and Bankowski, R. A.,** The effect of cobalt-60 on starlings *(Sturnus vulgaris vulgaris)*, *Avian Dis.*, 8(4), 555, 1964.
98. **Tester, J. R., McKinney, F., and Siniff, D. B.,** Mortality of three species of ducks — *Anas discors*, *A. crecca* and *A. clypeata* — exposed to ionizing radiation, *Radiat. Res.*, 33(2), 364, 1968.
99. **Tester, J. R. et al.,** Effects of ionizing radiation on pair-formation in the green-winged teal, *Anas crecca carolinensis*, in Effects of Ionizing Radiation and Other Environmental Factors on Breeding Behavior, Patterns and Movements of Selected Vertebrates, July 1966 through June 1967, U.S. AEC Rep. COO-1332-25, Prog. Rep. U.S. AEC, University of Minnesota Contract AT(11-1)-1332, University of Minnesota, Minneapolis, 1967, 6.

99a. **Tester, J. R. et al.,** Effect of ionizing radiation on territorial behavior in the shoveler, *Anas clypeata*, in Effects of Ionizing Radiation and Other Environmental Factors on Breeding Behavior, Patterns and Movements of Selected Vertebrates, July 1966 through June 1967, U.S. AEC Rep. COO-1332-25, Prog. Rep. U.S. AEC, University of Minnesota Contract AT(11-1)-1332, University of Minnesota, Minneapolis, 1967, 8.

99b. **Tester, J. R. et al.,** Effects of ionizing radiation in the blue-winged teal, *Anas discors*, in Effects of Ionizing Radiation and Other Environmental Factors on Breeding Behavior, Patterns and Movements of Selected Vertebrates, July 1966 through June 1967, U.S. AEC Rep. COO-1332-25, Prog. Rep. U.S. AEC, University of Minnesota Contract AT(11-1)-1332, University of Minnesota, Minneapolis, 1967, 11.

100. **Greb, R. J.,** Lethal X-ray dose in pheasants, *Proc. S. D. Acad. Sci.*, 34(1), 104, 1955.
101. **Stearner, S. P. et al.,** Acute radiation mortality in the parakeet, in Biological and Medical Research Division, Summary Report January through December 1960, U.S. AEC Rep. ANL-6368, Argonne National Laboratory, Illinois, 1961, 5.
102. **Sacher, G. A. and Staffeldt, E.,** Species differences in sensitivity of myomorph and sciuromorph rodents to life shortening by chronic gamma irradiation, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1042.
103. **Markham, O. D. and Whicker, F. W.,** Radiation $LD50_{(30)}$ of pikas *(Ochotona princeps)* in the natural environment and in captivity, *Am. Midl. Nat.*, 84(1), 248, 1970.
104. **Markham, O. D., Whicker, F. W., and Hansen, R. M.,** Radiation $LD50_{(30)}$ of Richardson ground squirrels, *Health Phys.*, 18(6), 731, 1970.
105. **Dunaway, P. B., Lewis, L. L., Story, J. D., Payne, J. A., and Inglis, J. M.,** Radiation effects in the Soricidae, Cricetidae, and Muridae, in Symposium on Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington, D. C., 1969, 173.
106. **DiGregorio, D., Dunaway, P. B., and Cosgrove, G. E.,** Effect of acute gamma irradiation on the reproduction of *Peromyscus leucopus*, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1076.
107. **Pelton, M. R. and Provost, E. E.,** Effects of radiation on reproduction of irradiated cotton rats *(Sigmodon hispidus)* trapped from enclosed areas of natural habitat, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D. C., 1973, 1048.
108. **Blair, W. F.,** Effects of x-irradiation on a natural population of the deer-mouse *(Peromyscus maniculatus)*, *Ecology*, 39(1), 113, 1958.
109. **Blair, W. F.,** Effects of radiation of natural populations of vertebrates, in *Recent Advances in Botany*, Vol. 2, University of Toronto Press, Canada, 1961, 1377.
110. **Golley, F. B. and Gentry, J. B.,** Response of rodents to acute gamma radiation under field conditions, in Symposium on Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1969, 166.

BEST AVAILABLE COPY

111. **O'Farrell, T. P., Hedlund, J. D., Olson, R. J., and Gilbert, R. O.,** Effects of ionizing radiation on survival, longevity, and reproduction in free-ranging pocket mice, *Perognathus parvus, Radiat. Res.*, 49(3), 611, 1972.
112. **Iverson, S. L. and Turner, B. N.,** Effects of acute irradiation on survival of captive and free-ranging meadow voles, in *Radioecology and Energy Resources*, Cushing, C. E., Jr. et al., Eds., Dowden, Hutchinson & Ross, Stroudsburg, Pa., 1976, 359.
113. **Markham, O. D. and Whicker, F. W.,** Intraspecific competition and response of pikas *(Ochotona princeps)* to radiation, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1070.
114. **Tryon, C. A. and Snyder, D. P.,** The effect of exposure to 200 and 400 R of ionizing radiation on the survivorship curves of the eastern chipmunk *(Tamias striatus)* under natural conditions, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1037.
115. **Snyder, D. P., Tryon, C. A., and Graybill, D. L.,** Effect of gamma radiation on range parameters in the eastern chipmunk, *Tamias striatus*, in *Radioecology and Energy Resources*, Cushing, C. E., Jr. et al., Eds., Dowden, Hutchinson & Ross, Stroudsburg, Pa., 1976, 354.
116. **Haley, T. J., Lindberg, R. G., Flesher, A. M., Raymond, K., McKibben, W., and Hayden, P.,** Response of the kangaroo rat *(Dipodomys merriami* Mearns) to single whole-body x-irradiation, *Radiat. Res.*, 12(1), 103, 1960.
117. **Kitchings, J. T., III, Dunaway, P. B., and Story, J. D.,** Blood changes in irradiated cotton rats and rice rats, *Radiat. Res.*, 42(2), 331, 1970.
118. **Dunaway, P. B., Story, J. D., and Kitchings, J. T.,** Radiation effects and radionuclide excretion in a natural population of pine voles, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1055.
119. **Barr, R. E. and Musacchia, X. J.,** Postirradiation hibernation and radiation response of ground squirrels: telemetry surveillance, *Radiat. Res.*, 51(3), 631, 1972.
120. **Sparrow, A. H.,** The role of the cell nucleus in determining radiosensitivity, U.S. AEC Rep. BNL 766(T-287), Brookhaven National Laboratory, Upton, Long Island, N.Y., 1962.
121. **Sparrow, R. C. and Sparrow, A. H.,** Relative radiosensitivities of woody and herbaceous spermatophytes, *Science*, 147(3664), 1449, 1965.
122. **Gunckel, J. E. and Sparrow, A. H.,** Ionizing radiations: biochemical, physiological and morphological aspects of their effects on plants, in *Encyclopedia of Plant Physiology*, Ruhland, W., Ed., Springer-Verlag, Berlin, 1961, 555.
123. **Osborne, T. S. and Constantin, M. J.,** Sensitivity to ionizing radiation: dormant seeds, in *Environmental Biology*, Altman, D. L. and Dittmer, D. S., Eds., American Society for Experimental Biology, Bethesda, Md., 1966, 183.
124. **Osborne, T. S. and Lunden, A. O.,** Seed radiosensitivity: a new constant?, *Science*, 145(3633), 710, 1964.
125. **Sparrow, A. H., Underbrink, A. G., and Sparrow, R. C.,** Chromosomes and cellular radiosensitivity. The relationship of D_o to chromosome volume and complexity in seventy-nine different organisms, *Radiat. Res.*, 32(4), 915, 1967.
126. **Polikarpov, G. G., Ed.,** Radioecological cytogenetics and problem of effect from small doses of ionizing radiation (in Russian), in *Marine Radioecology*, Naukova Dumka, Kiev, 1970, chap. 7; AEC-tr-7299 (English transl.), U.S. Atomic Energy Commission, Washington, D.C., 1972, 147.
127. **Tsytsugina, V. G., Risik, N. S., and Lazorenko, G. E.,** Karyology of marine fish and the effect of radionuclides on their chromosome apparatus, (in Russian), in *Artificial and Natural Radionuclides in Marine Life*, Naukova Dumka, Kiev, 1973, 26; English transl., TT-75-50010, 1975, 16.
128. **Blaylock, B. G.,** The production of chromosome aberration in *Chironomous riparius* (Diptera: Chironomidae) by tritiated water, *Can. Entomol.*, 103(3), 448, 1971.
129. **Walden, S. J.,** Effects of tritiated water on the embryonic development of the three-spine stickleback, *Casterosteus aculeatus* Linnaeus, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1087.
130. **Strand, J. A., Templeton, W. L., and Tangen, E. G.,** Accumulation and retention of tritium (tritiated water) in embryonic and larval fish, and radiation effect, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P1, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 445.
131. **Erickson, R. C.,** Effects of chronic irradiation by tritiated water on *Poecilia reticulata*, the guppy, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1091.
132. **Till, J. E.,** The effect of chronic exposure to ^{238}Pu(IV) citrate on the embryonic development of carp and fathead minnow eggs, *Health Phys.*, 34(4), 333, 1978.

133. **Nelson, V. A.**, Effects of strontium-90 + yttrium-90, zinc-65, and chromium-51 on the larvae of the Pacific oyster *Crassostrea gigas*, in *The Columbia River Estuary and Adjacent Ocean Waters: Bioenvironmental Studies*, Pruter, A. T. and Alverson, D. L., Eds., University of Washington Press, Seattle, 1972, 819.
134. **Bonham, K. and Donaldson, L. R.**, Sex ratios and retardation of gonadal development in chronically gamma-irradiated chinook salmon smolts, *Trans. Am. Fish. Soc.*, 101(3), 428, 1972.
135. **Cosgrove, G. E. and Blaylock, B. G.**, Acute and chronic irradiation effects in mosquito fish at 15 or 25°C, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P1, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 579.
136. **Marshall, J. S.**, The effects of continuous gamma radiation on the intrinsic rate of natural increase of *Daphnia pulex*, *Ecology*, 43(4), 598, 1962.
137. **Marshall, J. S.**, Population dynamics of *Daphnia pulex* as modified by chronic radiation stress, *Ecology*, 47(4), 561, 1966.
138. **Marshall, J. S.**, Radiation stress in exploited *Daphnia* populations, *Limnol. Oceanogr.*, 12(1), 154, 1967.
139. **Williams, R. B. and Murdoch, M. B.**, Effects of continuous low-level gamma radiation on sessile marine invertebrates, in Radioactive Contamination of the Marine Environment, Publ. STI/PUB/313, International Atomic Energy Agency, Vienna, 1973, 551.
140. **Williams, R. B. and Murdoch, M. B.**, The effects of continuous low level gamma radiation on estuarine microcosms, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1213.
141. **French, N. R. and Kaaz, H. W.**, The intrinsic rate of natural increase of irradiated *Peromyscus* in the laboratory, *Ecology*, 49(6), 1172, 1968.
142. **McCormick, J. F. and Platt, R. B.**, Effects of ionizing radiation on a natural plant community, *Radiat. Bot.*, 2(3/4), 161, 1962.
143. **Garrett, A.**, Compositional changes of ecosystems during chronic gamma irradiation, in Symposium on Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1969, 99.
144. **Styron, C. E.**, Ecology of two populations of an aquatic isopod (*Lirceus fontinalis* Raf.), with emphasis on ionizing radiation effects, in Symposium on Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1969, 53.
145. **Kratz, F. L.**, Radioresistance in natural populations of *Drosophila nebulosa* from a Brazilian area of high background radiation, *Mutat. Res.*, 27(3), 347, 1975.
146. **Verkhovskaya, I. N., Maslov, V. I., and Maslova, K. I.**, The action of minute doses of radiation and incorporated natural radioactive elements on spermatogenesis in *Microtus oeconomus* under natural conditions (in Russian), *Radiobiologiya*, 5(5), 720, 1965; English transl., AEC-tr-6602, U.S. Atomic Energy Commission, Washington, D.C., 1965, 133.
147. **Aliyev, A. T., Korzhuev, P. A., and Kashkin, K. P.**, Blood plasma proteins of the tundra vole *Microtus oeconomus*, living under conditions of increased natural background (in Russian), *Radiobiologiya*, 12(1), 63, 1972; English transl., AEC-tr-7316, U.S. Atomic Energy Commission, Washington, D.C., 1972, 91.
148. **Aliyev, A. T. and Kashkin, K. P.**, Blood plasma esterases of tundra voles (*Microtus oeconomus*), living under conditions of an increased natural background radiation (in Russian), *Radiobiologiya*, 13(4), 598, 1973; English transl., AEC-tr-7499, U.S. Atomic Energy Commission, Washington, D.C., 1974, 146.
149. **Aliyev, A. T. and Korzhuev, P. A.**, Amino acid composition of blood plasma proteins of root voles (*Microtus oeconomus* Pall.), living under various ecological conditions (in Russian), *Radiobiologiya*, 13(6), 818, 1973; AEC-tr-7534 (English transl.), U.S. Atomic Energy Commission, Washington, D.C., 1973, 10.
150. **Osburn, W. S.**, Variation in clones of Penstemon growing in natural areas of differing radioactivity, *Science*, 134(3475), 342, 1961.
151. **Mericle, L. W. and Mericle, R. P.**, Biological discrimination of differences in natural background radiation level, *Radiat. Bot.*, 5(6), 475, 1965.
152. **Mericle, L. W. and Mericle, R. P.**, Somatic mutations in clone 02 *Tradescantia*. A search for genetic diversity, *J. Hered.*, 62(6), 323, 1971.
153. **Nayar, G. G., George, K. P., and Gopal-Ayengar, A. R.**, On the biological effects of high background radioactivity: studies on *Tradescantia* grown in radioactive monazite sand, *Radiat. Bot.*, 10(2), 287, 1970.
154. **Gopal-Ayengar, A. R., Nayar, G. G., George, K. P., and Mistry, K. B.**, Biological effects of high background radioactivity: studies on plants growing in the monazite-bearing areas of Kerala Coast & adjoining regions, *Indian J. Exp. Biol.*, 8(Oct.), 313, 1970.

155. **Sarosiek, J. and Wozakowska-Natkaniec, H.,** Response of *Marchantia polymorpha* L. to chronic gamma radiation under natural conditions, *Acta Soc. Bot. Pol.*, 36(1), 187, 1967.
156. **Sarosiek, J., Kola, W., and Orda, A.,** The radioecology of *Pogonatum urnigerum* (L.). Pal. Beauv., *Acta Soc. Bot. Pol.*, 42(2), 241, 1973.
157. **Blaylock, B. G.,** Chromosomal aberrations in a natural population of *Chironomus tentans* exposed to chronic low-level radiation, *Evolution*, 13(3), 421, 1965.
158. **Schreckhise, R. G. et al.,** Radioecology of nuclear fuel cycles, in Pacific Northwest Laboratory Annual Report for 1978, Part 2, Ecological Sciences, U.S. DOE Rep. PNL-2850 PT2, Vaughan, B. G. et al., Eds., Pacific Northwest Laboratory, Richland, Wash., 1979, 5.18.
159. **Evenson, L. M., Olson, D. P., Halford, D. K., and Markham, O. D.,** Systemic effects of radiation exposure on rodents inhabiting liquid and solid radioactive waste disposal areas, in Ecological Studies on the Idaho Engineering Laboratory Site, U.S. DOE report IDO-12087, Markham, O. D., Ed., Idaho Falls, 1978, 99.
160. **Dahlman, R. C., Auerbach, S. I., and Dunaway, P. B.,** Behaviour of ^{137}Cs-tagged particles in a fescue meadow, in Environmental Contamination by Radioactive Materials, Publ. STI/PUB/226, International Atomic Energy Agency, Vienna, 1969, 153.
161. **Styron, C. E., Dodson, G. J., Beauchamp, J. J., and Miller, F. L., Jr.,** Responses of a grassland arthropod community to chronic beta and gamma radiation, in *Radioecology and Energy Resources*, Cushing, C. E., Jr. et al., Eds., Dowden, Hutchinson & Ross, Stroudsburg, Pa., 1976, 381.
162. **Aleksakhin, R. M., Karaban, R. T., Kulikov, N. V., Molchanov, A. A., Naryschkin, M. A., Tarchevskaya, S. V., Tikhomirov, F. A., Tyuryukanova, E. B., and Yushkov, P. I.,** Some aspects of radioactive fission products migration in the forest biogeocenoses and the effects of ionizing radiations on the woody plants, in *Actes Symp. Int. Radioecol.*, Vol. 2, Commissariat a l'Energie Atomique, Cadarache, France, 1970, 999; *Nucl. Sci. Abstr.*, 24(20), 41788, 1970.
163. **Cherezhanova, L. V. and Aleksakhin, R. M.,** Cytogenetic effects of long-term irradiation on natural plant populations (in Russian), *Zh. Obshch. Biol.*, 32(4), 494, 1971. (English summary.)
164. **Il'yenko, A. I.,** Infestation of small mammals with gamasid ticks on plots contaminated with ^{90}Sr (in Russian), *Zool. Zh.*, 50(2), 243, 1971. (English summary.)
165. **Isaev, S. I.,** Ecological problems in the reproduction of wild rodents and contamination of the habitat with Sr^{90} (in Russian), *Ekologiya*, 6(1), 46, 1975; *English transl.*, *Sov. J. Ecol.*, 6(1), 33.
166. **Zavitkovski, J., Ed.,** The Enterprise, Wisconsin, Radiation Forest. Radioecological Studies, U.S. ERDA Rep. TID-26113-P2, U.S. Energy Research and Development Administration, Washington, D.C., 1977.
167. **Woodwell, G. M.,** Radiation and the patterns of nature, *Science*, 156(3774), 461, 1967.
168. **Woodwell, G. M. and Rebuck, A. L.,** Effects of chronic gamma radiation on the structure and diversity of an oak-pine forest, *Ecol. Monogr.*, 37(1), 53, 1967.
169. **Brodo, I. M.,** Field studies of the effects of ionizing radiation on lichens, *Bryologist*, 67(1), 76, 1964.
170. **Woodwell, G. M. and Gannutz, T. P.,** Effects of chronic gamma irradiation on lichen communities of a forest, *Am. J. Bot.*, 54(10), 1210, 1967.
171. **Foreman, R. T. T. and Woodwell, G. M.,** Effects of chronic gamma irradiation on bryophyte populations of a forest ecosystem, *Bull. Ecol. Soc. Am.*, 48(2) (Abstr.), 68, 1967.
172. **Gochenauer, S. E. and Woodwell, G. M.,** Effects of chronic gamma irradiation on the soil microfungi of an oak-pine forest, *Am. J. Bot.*, 57(6) (Abstr.), 746, 1970.
173. **Woodwell, G. M. and Holt, B. R.,** Effect of nuclear war on the structure and function of natural communities: an appraisal based on experiments with gamma radiation, in Survival of Food Crops and Livestock in the Event of Nuclear War *(AEC Symp. Ser. 24)*, U.S. AEC Rep. CONF-700909, Bensen, D. W. and Sparrow, A. H., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1971, 482.
174. **Franz, E. H. and Woodwell, G. M.,** Effects of chronic gamma irradiation on the soil algal community of an oak-pine forest, *Radiat. Bot.*, 13(6), 323, 1973.
175. **Platt, R. B.,** Ionizing radiation and homeostasis of ecosystems, in Ecological Effects of Nuclear War, U.S. AEC Rep. BNL 917(C-43), Woodwell, G. M., Ed., Brookhaven National Laboratory, Upton, Long Island, N.Y., 1965, 39.
176. **Stanovick, R., Giddens, J., and McCreery, R. A.,** Effect of ionizing radiation on soil microorganisms, *Soil Sci.*, 92(3), 183, 1961.
177. **Desmarais, A. P. and Helmuth, B. T.,** Effects of ^{137}Cs radiation on vegetation structure and optical density at El Verde, in A Tropical Rain Forest: A Study of Irradiation and Ecology at El Verde, Puerto Rico, U.S. AEC Rep. TID-24270(PRNC-138), Odum, H. T. and Pigeon, R. F., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1970, D77.
178. **Smith, R. F.,** The vegetation structure of a Puerto Rican rain forest before and after short-term gamma irradiation, in A Tropical Rain Forest: A Study of Irradiation and Ecology at El Verde, Puerto Rico, U.S. AEC Rep. TID-24270(PRNC-138), Odum, H. T. and Pigeon, R. F., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1970, D103.

179. **Witkamp, M.,** Aspects of soil microflora in a gamma-irradiated rain forest, in A Tropical Rain Forest: A Study of Irradiation and Ecology at El Verde, Puerto Rico, U.S. AEC Rep. TID-24270(PRNC-138), Odum, H. T. and Pigeon, R. F., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1970, F29.
180. **Holler, J. R. and Cowley, G. T.,** Response of soil, root, and litter microfungal populations to radiation, in A Tropical Rain Forest: A Study of Irradiation and Ecology at El Verde, Puerto Rico, U.S. AEC Rep. TID-24270(PRNC-138), Odum, H. T. and Pigeon, R. F., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1970, F35.
181. **Fabries, M., Grauby, A., and Trochain, J. L.,** Study of a Mediterranean type phytocenose subjected to chronic gamma radiation, *Radiat. Bot.*, 12(3), 125, 1972.
182. **Saas, A., Bovard, P., and Grauby, A.,** Effect of chronic gamma irradiation on decay of oak *(Quercus pubescens* Willd) and dogwood *(Cornus mas* L.) leaves and subjacent litter, *Radiat. Bot.*, 15(2), 141, 1975.
183. **Fraley, L., Jr. and Whicker, F. W.,** Response of shortgrass plains vegetation to gamma radiation. I. Chronic irradiation, *Radiat. Bot.*, 13(6), 331, 1973.
184. **Fraley, L., Jr. and Whicker, F. W.,** Response of shortgrass plains vegetation to gamma radiation. II. Short-term seasonal irradiation, *Radiat. Bot.*, 13(6), 343, 1973.
185. **Sparrow, S., Jr.,** Chronic Gamma Radiation Stress on Soil Microorganisms of a Grassland, M.S. thesis, Colorado State University, Fort Collins, 1973.
186. **Zavitkovski, J.,** Structural and floristic changes caused by gamma radiation in understory vegetation of two forest types in northern Wisconsin, in The Enterprise, Wisconsin, Radiation Forest: Radioecological Studies, U.S. ERDA Rep. TID-26113-P2, Zavitkovski, J., Ed., U.S. Energy Research and Development Administration, Washington, D.C., 1977, 49.
187. **Woodwell, G. M. and Oosting, J. K.,** Effects of chronic irradiation on the development of old field plant communities, *Radiat. Bot.*, 5(3), 205, 1965.
188. **Daniel, C. P.,** A study of succession in fields irradiated with fast neutron and gamma radiation, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 277.
189. **Daniel, C. P. and Platt, R. B.,** Direct and indirect effects of short term ionizing radiation on old field succession, *Ecol. Monogr.*, 38(1), 1, 1968.
190. **Monk, C. D.,** Effects of short-term gamma irradiation on an old field, *Radiat. Bot.*, 6(4), 329, 1966.
191. **Miller, G. L.,** The influence of season on radiation sensitivity on an old field community, Ph. D. dissertation, University of North Carolina, Chapel Hill, 1968; *Diss. Abstr*, 29(12), 4551-B.
192. **Odum, H. T.,** Summary: an emerging view of the ecological system at El Verde, in A Tropical Rain Forest: A Study of Irradiation and Ecology at El Verde, Puerto Rico, U.S. AEC Rep. TID-24270(PRNC-138), Odum, H. T. and Pigeon, R. F., U.S. Atomic Energy Commission, Washington, D.C., 1970, I191.
193. **Woodwell, G. M.,** Effects of ionizing radiation on terrestrial ecosystems, *Science*, 138(3540), 572, 1962.
194. **Woodwell, G. M. and Miller, L. N.,** Chronic gamma radiation affects the distribution of radial increments in *Pinus rigida* stems, *Science*, 139(3551), 222, 1963.
195. **Bourdeau, P. F. and Woodwell, G. M.,** Field measurements of carbon dioxide exchange in *Pinus rigida* trees exposed to chronic gamma irradiation, *Ecology*, 45(2), 403, 1964.
196. **Woodwell, G. M. and Marples, T. G.,** The influence of chronic gamma irradiation on production and decay of litter and humus in an oak-pine forest, *Ecology*, 49(3), 456, 1968.
197. **McGinnis, J. T.,** Effects of radiation from an air-shielded reactor on forest litter production, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 283.
198. **Wiegert, R. G.,** Effects of ionizing radiation on leaf fall, decomposition, and litter microarthropods of a montane rain forest, in A Tropical Rain Forest: A Study of Irradiation and Ecology at El Verde, Puerto Rico, U.S. AEC Rep. TID-24270(PRNC-138), Odum, H. T. and Pigeon, R. F., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1970, H89.
199. **Zavitkovski, J. and Salmonson, B. J.,** Effects of gamma radiation on biomass production of ground vegetation under broadleaved forests of northern Wisconsin, in The Enterprise, Wisconsin, Radiation Forest: Radioecological Studies, U.S. ERDA Rep. TID-26113-P2, Zavitkovski, J., Ed., U.S. Energy Research and Development Administration, Washington, D.C., 1977, 35.
200. **Fraley, L., Jr.,** Response of shortgrass plains vegetation to chronic and seasonally administered gamma radiation, Ph. D. dissertation, Colorado State University, Fort Collins, 1971; *Diss. Abstr.*, 32(11), 6714-B.
201. **Mergen, F. and Simpson, B. A.,** Effect of ionizing radiation on megasporogenesis in *Pinus rigida* (Mill), *Radiat. Bot.*, 7(3), 247, 1967.
202. **Mergen, F. and Johansen, T. S.,** Effect of ionizing radiation on seed germination and seedling growth of *Pinus rigida* (Mill), *Radiat. Bot.*, 4(4), 417, 1964.

203. **Mergen, F. and Stairs, G. R.,** Low level chronic gamma irradiation of a pitch pine-oak forest — its physiological and genetical effects on reproduction, *Radiat. Bot.*, 2(3/4), 205, 1962.
204. **Clark, A., III and Hamilton, J. R.,** Effects of ionizing irradiation on the xylem derivatives of *Pinus echinata* Mill, *West Va. Univ. Agric. Exp. Stan. Bull.*, 567T, 1968.
205. **Mericle, L. W., Mericle, R. P., and Sparrow, A. H.,** Cumulative radiation damage in oak trees, *Radiat. Bot.*, 2(4), 265, 1962.
206. **Witherspoon, J. P. and Taylor, E. G., Jr.,** Radiation-induced anatomical modifications in forest trees, *J. Tenn. Acad. Sci.*, 44(4), 118, 1969.
207. **McCormick, J. F. and McJunkin, R. E.,** Interactions of gamma radiation and other environmental stresses upon pine seeds and seedlings, *Health Phys.*, 11(12), 1643, 1965.
208. **McCormick, J. F.,** Effects of ionizing radiation on a pine forest, in Symposium on Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1969, 78.
209. **Sparrow, A. H., Sparrow, R. C., Thompson, K. H., and Schairer, L. A.,** The use of nuclear and chromosomal variables in determining and predicting radiosensitivities, in *The Use of Induced Mutations in Plant Breeding*, Pergamon Press, Elmsford, New York, 1965, 101.
210. **Odum, E. P.,** Summary, in Ecological Effects of Nuclear War, U.S. AEC Rep. BNL-917(C-43), Woodwell, G. M., Ed., Brookhaven National Laboratory, Upton, Long Island, N.Y., 1965, 69.
211. **Chappell, H. G.,** The effect of ionizing radiation on *Smilax* with special reference to the protection afforded by their underground vegetative structures, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 289.
212. **Cotter, D. J. and McGinnis, J. T.,** Recovery of hardwood stands 3—5 years following acute irradiation, *Health Phys.*, 11(12), 1663, 1965.
213. **Jordan, C. F.,** Recovery of a tropical rain forest after gamma irradiation, in Symposium on Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1969, 89.
214. **Woodwell, G. M. and Sparrow, A. H.,** Effects of ionizing radiation on ecological systems, in Ecological Effects of Nuclear War, U.S. AEC Rep. BNL-917(C-43), Woodwell, G. M., Ed., Brookhaven National Laboratory, Upton, Long Island, N.Y., 1965, 20.
215. **Zavitkovski, J.,** Effects of gamma radiation on a northern forest ecosystem: a summary, in The Enterprise, Wisconsin, Radiation Forest: Radioecological Studies, U.S. ERDA Rep. TID-26113-P2, Zavitkovski, J., Ed., U.S. Energy Research and Development Administration, Washington, D.C., 1977, 197.
216. **Wagner, R. H. and Marples, T. G.,** The breeding success of various passerine birds under chronic gamma irradiation stress, *Auk*, 83(3), 437, 1966.
217. **Bongiorno, S. F. and Pearson, P. G.,** Orientation of *Peromyscus* in relation to chronic gamma radiation and vegetation, *Am. Midl. Nat.*, 72(1), 82, 1964.
218. **Woodwell, G. M. and Brower, J. M.,** An aphid population explosion induced by chronic gamma irradiation of a forest, *Ecology*, 48(4), 680, 1967.
219. **Brower, J. H.,** Behavioral changes in an ant colony exposed to chronic gamma irradiation, *Am. Midl. Nat.*, 75(2), 530, 1966.
220. **Turner, F. B., Medica, P. A., Lannom, J. R., Jr., and Hoddenbach, G. A.,** A demographic analysis of continuously irradiated and nonirradiated populations of the lizard, *Uta stansburiana*, *Radiat. Res.*, 38(2), 349, 1969.
221. **McKinney, C. O. and Turner, F. B.,** Genetic variation in irradiated and nonirradiated populations of the lizard, *Uta stansburiana*, *Radiat. Res.*, 47(2), 530, 1971.
222. **Turner, F. B. and Medica, P. A.,** Sterility among female lizards *(Uta stansburiana)* exposed to continuous γ — irradiation, *Radiat. Res.*, 70(1), 154, 1977.
223. **Turner, F. B., Licht, P., Thrasher, J. D., Medica, P. A., and Lannom, J. R., Jr.,** Radiation induced sterility in natural populations of lizards *(Crotaphytus wislizenii* and *Cnemidophorus trigris)*, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-71050-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1131.
224. **French, N. R.,** Description of a study of ecological effects of a desert area from chronic exposure to low level ionizing radiation, U.S. AEC Rep. UCLA 12-532, University of California, Los Angeles, 1964.
225. **Schnell, J. H.,** The effect of neutron-gamma radiation on free-living small mammals at the Lockheed Reactor Site, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 339.
226. **Schnell, J. H.,** Some effects of neutron-gamma radiation on late summer bird populations, *Auk*, 81(4), 528, 1964.
227. **Cadwell, L. L.,** Colony formation of the western harvester ant in a chronic gamma radiation field, *Am. Midl. Nat.*, 89(2), 446, 1973.

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228. **Cadwell, L. L. and Whicker, F. W.,** Radiation effects on a shortgrass plains ecosystem: the arthropod community, in Radioecology of Some Natural Organisms and Systems in Colorado, U.S. AEC Rep. COO-1156-54, 10th Technical Prog. Rep. U.S. Atomic Energy Commission, Contract AT(11-1)-1156, Colorado State University, Fort Collins, 1972, 38.
229. **McMahan, E. A. and Sollins, N. F.,** Diversity of microarthropods after irradiation, in A Tropical Rain Forest: A Study of Irradiation and Ecology at El Verde, Puerto Rico, U.S. AEC Rep. TID-24270(PRNC-138), Odum, H. T. and Pigeon, R. F., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1970, E151.
230. **McMahan, E. A.,** Radiation and termites at El Verde, in A Tropical Rain Forest: A Study of Irradiation and Ecology at El Verde, Puerto Rico, U.S. AEC Rep. TID-24270(PRNC-138), Odum, H. T. and Pigeon, R. F., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1970, E105.
231. **Weinbren, M. P. and Weinbren, B. M.,** Observations on the mosquito population in the irradiated forest at El Verde, in A Tropical Rain Forest: A Study of Irradiation and Ecology at El Verde, Puerto Rico, U.S. AEC Rep. TID-24270(PRNC-138), Odum, H. T. and Pigeon, R. F., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1970, E159.
232. **Heatwole, H., Rossy, A., Colorado, I., and Amadeo, R.,** Effects of radiation on a population of the Puerto Rican tree snail, *Caracolus caracolla*, in A Tropical Rain Forest: A Study of Irradiation and Ecology in El Verde, Puerto Rico, U.S. AEC Rep. TID-24270(PRNC-138), Odum, H. T. and Pigeon, R. F., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1970, E17.
233. **Turner, F. B. and Gist, C. S.,** Observations of lizards and tree frogs in a irradiated Puerto Rican forest, in A Tropical Rain Forest: A Study of Irradiation and Ecology at El Verde, Puerto Rico, U.S. AEC Rep. TID-24270(PRNC-138), Odum, H. T. and Pigeon, R. F., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1970, E25.
234. **Recher, H. F.,** Population density and seasonal changes of the avifauna in a tropical forest before and after gamma irradiation, in A Tropical Rain Forest: A Study of Irradiation and Ecology at El Verde, Puerto Rico, U.S. AEC Rep. TID-24270(PRNC-138), Odum, H. T. and Pigeon, R. F., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1970, E69.
235. **Weinbren, M. P., Weinbren, B. M., Jackson, W. B., and Villella, J. B.,** Studies on the roof rat *(Rattus rattus)* in the El Verde Forest, in A Tropical Rain Forest: A Study of Irradiation and Ecology at El Verde, Puerto Rico, U.S. AEC Rep. TID-24270(PRNC-138), Odum, H. T. and Pigeon, R. F., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1970, E169.
236. **Buech, R. R.,** Small mammals in a gamma-irradiated northern forest community, in The Enterprise, Wisconsin, Radiation Forest: Radioecological Studies, ERDA Rep. TID-26113-P2, Zavitkovski, J., Ed., Energy Research and Development Administration, Washington, D.C., 1977, 167.
237. **Buech, R. R.,** Observations of nesting avifauna under gamma-radiation exposure, in The Enterprise, Wisconsin, Radiation Forest: Radioecological Studies, ERDA Rep. TID-26113-P2, Zavitkovski, J., Ed., Energy Research and Development Administration, Washington, D.C., 1977, 181.
238. **Bonham, K. and Donaldson, L. R.,** Low-level chronic irradiation of salmon eggs and alevins, in Disposal of Radioactive Wastes into Seas, Oceans and Surface Waters, Publ. STI/PUB/126, International Atomic Energy Agency, Vienna, 1966, 869.

ADDITIONAL READINGS

Badr, F. M. and Badr, R. S., Effect of x-irradiation on mitotic activity of bone marrow cells of laboratory and wild rats, *Folia Biol. (Prague)*, 17(4), 258, 1971.

Belyaev, V. A. and Maslov, V. I., Application of cytogenetic methods in radioecological studes (in Russian), in *Methods of Radioecological Investigations*, Verkovskaya, I. N., Ed., Atomizdat, Moscow, 1971, 176; *Nucl. Sci. Abstr.*, 16(6), 12255.

Berry, R. J., Beechey, C. V., and Searle, A. G., Cytogenetic radiosensitivity and chiasma frequency in wild and laboratory mice, *Mutat. Res.*, 19(1), 129, 1973.

Bigot, L., Grauby, A., Poinsot, N., Rougon, G., and Tchernia, F., Effect of chronic γ—irradiation on the wild life and microplant life of a wooded ecosystem at Cadarache (in French), *Radioprotection*, 8(4), 243, 1973; *Nucl. Sci. Abstr.*, 30(7), 18895.

Breslavets, L. B., *Plants and X Rays*, Academy of Sciences, U.S.S.R., Moscow, 1946; *Plants and X Rays* (English transl.), Sparrow, A. H., Ed., American Institute of Biological Sciences, Washington, D.C., 1960.

Brower, J. H., Developmental success of two species of *Ips* (Coleoptera: Scolytidae) in a chronically irradiated forest community, *Can. Entomol.*, 106(3), 233, 1974.

Brown, F. A., Jr. and Park, Y. H., Seasonal variations in sign and strength of gamma-taxis in planarians, *Nature (London)*, 202(4931), 469, 1964.

Brown, V. M. and Templeton, W. L., Resistance of fish embryos to chronic irradiation, *Nature (London)*, 203(4951), 1257, 1964.

Buech, R. R., Sensitivity of the red-backed vole *(Clethrionomys g. gapperi)* to acute gamma radiation, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1082.

Buech, R. R., Radiosensitivity and recovery of tree crowns in a gamma-irradiated northern forest community, in The Enterprise, Wisconsin, Radiation Forest: Radioecological Studies, U.S. ERDA Rep. TID-26113-P2, Zavitkovski, J., Ed., U.S. Energy Research and Development Administration, Washington, D.C., 1977, 79.

Buech, R. R. and Salmonson, B. J., Tree-shoot elongation patterns in a gamma-irradiated northern forest community, in The Enterprise, Wisconsin, Radiation Forest: Radioecological Studies, U.S. ERDA Rep. TID-26113-P2, Zavitkovski, J., Ed., U.S. Energy Research and Development Administration, Washington, D.C., 1977, 91.

Buech, R. R. and Salmonson, B. J., Tree phenology in gamma-irradiated northern forest community, in The Enterprise, Wisconsin, Radiation Forest: Radioecological Studies, Zavitkovski, J., Ed., U.S. ERDA Rep. TID-26113-P2, U.S. Energy Research and Development Administration, Washington, D.C., 1977, 141.

Cavalloro, R. and Delrio, G., Population longevity in gamma-irradiated *Collembola, Int. Appl. Radiat. Isotop.*, 22(3), 216, 1971.

Clark, B. W. and Coleman, D. C., A comparative study of the effects of acute and chronic gamma irradiation on total soil respiration, *Pedobiologia*, 10, 199, 1970.

Comar, C. L., Presentation of U.S.A. National Academy of Sciences report on the effects on populations of exposure to low levels of ionizing radiation (BEIR Rep.). I. General review and implications, in Proc. 3rd Int. Congr. Int. Radiation Protection Association, U.S. AEC Rep. CONF-730907-P1, 1974, 28; *Nucl. Sci. Abstr.*, 30(10), 27059.

Cooley, A. D. and Clinton, J. H., Nuclear volumes, DNA contents, and radiosensitivity in whole-body irradiated amphibians, *Radiat. Res.*, 54(1), 69, 1973.

Cosgrove, G. E., Blaylock, B. G., Ulrikson, G. U., and Cohan, P. H., Radiation-induced hematopoietic lesions in fish, in *Pathology of Fishes*, Ribelin, W. E. and Migaki, G., Eds., University of Wisconsin Press, Madison, 1975, 463.

Crow, J. F., Presentation of the U.S.A. National Academy of Sciences report on the effects on populations of exposure to low levels of ionizing radiation (BEIR report). II. Genetic effects, in Proc. 3rd Int. Congr. Int. Radiation Protection Association, U.S. AEC Rep. CONF-730907-P1, 1974, 37; *Nucl. Sci. Abstr.*, 30(10), 27060.

Crow, T. R., Effects of gamma radiation on the biomass structure of the arboreal stratum in a northern forest, in The Enterprise, Wisconsin, Radiation Forest: Radioecological Studies, U.S. ERDA Rep. TID-26113-P2, Zavitkovski, J., Ed., U.S. Energy Research and Development Administration, Washington, D.C., 1977, 69.

Dahlman, R. C., Beauchamp, J. J., and Tanaka, Y., Effects of simulated fallout radiation on reproductive capacity of fescue, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P1, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 988.

Darenskaja, N. G., Kuznecova, S. S., Pravdina, G. M., and Ezova, V., Seasonal changes of radiosensitivity in mice (in German), *Radiobiol. Radiother.*, 15(3), 399, 1974; *Nucl. Sci. Abstr.*, 31(3), 6333.

Dubinin, N. P., *Radiation and Evolution of Populations* (in Russian), Atomizdat, Moscow, 1966; *Nucl. Sci. Abstr.*, 22(10), 40655.

Ducoff, H. S., Causes of death in irradiated adult insects, *Biol. Rev.*, 47, 211, 1972.

Dyer, K. F., The effect of radiation on small competing populations of *Drosophila melanogaster*. I. The accumulation of genetic damage, *Genetics*, 61(1), 227, 1969.

Dyer, K. F., The effect of radiation on small competing populations of *Drosophila melanogaster*. II. The changing frequencies of autosomal recessive lethals, *Genetics*, 61(1), 245, 1969.

Dyer, K. F., The effect of radiation on small competing populations of *Drosophila melanogaster*. III. Changes in competitive ability, *Genetics*, 61(1), 275, 1969.

Egami, N., Kinetics of recovery from injury after whole-body x-irradiation of the fish *Oryzias latipes* at different temperatures, *Radiat. Res.*, 37(1), 192, 1969.

Egami, N., Hereditary effects of external radiation (in Japanese), in *Radioactivity of Fishes. Contamination, Injuries, and Utilization*, Egami, N., Ed., Koseisha Kosei Kaku, Tokyo, 1973, 174. (NSA 29(6): 13025).

Egami, N. and Eto, K., Somatic effect of external irradiation on mature fish (compendium) (in Japanese), in *Radioactivity and Fishes. Contamination, Injuries, and Utilization*, Egami, N., Ed., Koseisha Kosei Kaku, Tokyo, 1973, 65.; *Nucl. Sci. Abstr.*, 29(6), 13024.

Egami, N., Eto, K., and Taguchi, Y., Effects of external irradiation on the bodies of adult fishes (consideration in detail) (in Japanese), in *Radioactivity and Fishes. Contamination, Injuries, and Utilization*, Egami, N., Ed., Koseisha Kosei Kaku, Tokyo, 1973, 92; *Nucl. Sci. Abstr.*, 29(6) 13023.

El-Lakany, M. H., The effects of ionizing radiation on forest trees; a review, Rep. AECL-3951, Whiteshell Nuclear Research Establishment, Atomic Energy of Canada Limited, Pinawa, Manitoba, 1971.

Engel, D. W., The radiation sensitivities of three species of fiddler crabs *(Uca pugilator, U. pugnax,* and *U. minax), Chesapeake Sci.*, 14(4), 289, 1973.

Engel, D. W., Davis, E. M., Angelovic, J. W., and Smith, D. E., Effect of radiation, salinity, and temperature on the ionic regulation of the blue crab, *Callinectes sapidus*, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1113.

Eto, K., Effect of external irradiation on fish eggs and embryo (in Japanese), in *Radioactivity and Fishes. Contamination, Injuries, and Utilization*, Egami, N., Ed., Koseisha Kosei Kaku, Tokyo, 1973, 202; *Nucl. Sci. Abstr.*, 29(7), 16005.

Eto, K., Effect of internal irradiation on fish (in Japanese), in *Radioactivity and Fishes. Contamination, Injuries, and Utilization*, Egami, N., Ed., Koseisha Kosei Kaku, Tokyo, 1973, 298; *Nucl. Sci. Abstr.*, 29(5), 10474.

Etoh, H., Hyodo-Taguchi, Y., and Maruyama, T., Effects of x-irradiation of a part of the body on mortality rate and on histological changes in goldfish, *Carassius auratus*, *J. Radiat. Res.*, 9(3/4), 141, 1968.

Fedorova, G. V., The biological effect of radiocarbon (C^{14}) on fish in the early development stages (English transl.), *J. Ichtyol. (USSR)*, 12(1), 173, 1972.

Flaccus, E., Armentano, T. V., and Archer, M., Effects of chronic gamma radiation on the composition of the herb community of an oak-pine forest, *Radiat. Bot.*, 14(4), 263, 1974.

Foster, R. F., Ophel, I. L., and Preston, A., Evaluation of human radiation exposure, in *Radioactivity in the Marine Environment*, Panel on Radioactivity in the Marine Environment, National Academy of Sciences, Washington, D.C., 1971, 240.

Golley, F. B., Gentry, J. B., Menhinick, E. F., and Carmon, J. L., Response of wild rodents to acute gamma radiation, *Radiat. Res.*, 24(2), 350, 1965.

Gorodilov, Yu. N., Change in radioresistance of some species of salmon in the early stages of embryonal development, (in Russian), *Radiobiologiya*, 11(6), 930, 1971; English transl., AEC-tr-7307, U.S. Atomic Energy Commission, Washington, D.C., 159.

Grayum, M. M., Effects of thermal shock and ionizing radiation on primary productivity, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P1, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 639.

Halford, D. K. and Markham, O. D., Radiation dosimetry of small mammals inhabiting a liquid radioactive waste disposal area, *Ecology*, 59(5), 1047, 1978.

Harris, W. F. and Witherspoon, J. P., Effects of ionizing radiation on processes influencing tolerance of tree seedlings, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P1, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 961.

Holton, R. L., Osterberg, C. L., and Forster, W. O., Effect of gamma irradiation on the reproductive performance of *Artemia* as determined by individual pair matings, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Comission, Washington, D.C., 1973, 1191.

Hoppenheit, M., Effects of fecundity and fertility of single sub-lethal x-irradiation of *Gammarus duebeni* females, in Radioactive Contamination of the Marine Environment, Publ. STI/PUB/313, International Atomic Energy Agency, Vienna, 1973, 479.

Hyodo-Taguchi, Y. and Egami, N., Change in dose-survival time relationship after x-irradiation during embryonic development in the fish, *Oryzias latipes*, *J. Radiat. Res.*, 10(3/4), 121, 1969.

Jaroslow, B. N., Smith, D. E., Williams, M., and Tyler, S. A., Survival of hibernating ground squirrels *(Citellus tridecemlineatus)* after single and fractionated doses of cobalt-60 gamma radiation, *Radiat. Res.*, 38(2), 379, 1969.

Jones, J. M. and Platt, R. B., Effects of ionizing radiation, climate, and nutrition on growth and structure of a lichen *Parmelia conspersa* (ACH.) ACH., in Symposium on Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1969, 111.

Jordan, C. F., Respiration rates of red pine along a gradient of gamma radiation following eight years of exposure, *Radiat. Bot.*, 14(4), 337, 1974.

Kellogg, F. E., Provost, E. E., and Pelton, M. R., Determination of a cobalt-60 $LD_{50(30)}$ for the wild-caught cotton rat *(Sigmodon hispidus)*, *Radiat. Res.*, 35(2), 458, 1968.

Korotkova, G. P. and Tokin, B. P., On the reaction of sponges and coelenterates to β irradiation (in Russian), *Radiobiologiya*, 5(2), 190, 1965; English transl., AEC-tr-6599, U.S. Atomic Energy Commission, Washington, D.C., 1965, 40.

Kulikov, N. V., Radioecology of freshwater plants and animals (in Russian), in *Contemporary Problems of Radiobiology*, Vol. 2, Klechkovskiy, V. M., Polikarpov, G. G., and Aleksakhin, R. M., Eds., Atomizdat, Moscow, 1971, 367; English transl., *Radioecology*, Greenberg, D., Ed., John Wiley & Sons, New York, 1973, 323.

Lynn, M., Ionizing radiations in forests and forestry (excluding the use of radio-active tracers), *For. Abstrs.*, 28(1), 1, 1967.

McCormick, J. F., Effects of ionizing radiation on a pine forest, in Symposium on Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1969, 78.

Medica, P. A., Turner, F. B., and Smith, D. D., Effects of radiation on a fenced population of horned lizards *(Phrynosoma platyrhinos)* in southern Nevada, *J. Herpetol.*, 7(2), 79, 1973.

Menhinick, E. F. and Crossley, D. A., Jr., Radiation sensitivity of twelve species of arthropods, *Ann. Entomol. Soc. Am.*, 62(4), 711, 1969.

Mergen, F. and Stairs, G. R., The effect of ionizing radiation on the reproductive capacity of forest trees, *Health Phys.*, 19(1), 37, 1970.

Mericle, L. W. and Mericle, R. P., Reassessing the biological role of background terrestrial radiation as a constituent of the natural environment, *Health Phys.*, 11(12), 1607, 1965.

Palumbo, R. F., Recovery of the land plants at Eniwetok Atoll following a nuclear detonation, *Radiat. Bot.*, 1(2), 182, 1962.

Patel, S. and Patel, B., Effect of ionizing radiation on the blood of a marine polychaete worm *Marphysa mossambica* Peters, in Radionuclides in Ecosystems, U.S. AEC Rep. CONF-710501-P2, Nelson, D. J., Ed., U.S. Atomic Energy Commission, Washington, D.C., 1973, 1206.

Pearson, A. K., Licht, P., Nagy, K. A., and Medica, P. A., Endocrine function and reproductive impairment in an irradiated population of the lizard *Uta stansburiana*, *Radiat. Res.*, 76(3), 610, 1978.

Pechkurenkov, V. L., Shekhanova, I. A., and Telysheva, I. G., The effect of chronic small dose irradiation on the embryonic development of fishes and the validity of various assessment methods (English transl.), *J. Ichtyol. USSR*, 12(1), 71, 1972.

Prasad, N., Bushong, S. C., North, L. B., and Thornby, J., Radiation lethality in the opossum, *Radiat. Res.*, 68(3), 514, 1976.

Preston, A. and Jefferies, D. F., Aquatic aspects of chronic and acute contamination situations, in Environmental Contamination by Radioactive Materials, Publ. STI/PUB/226, International Atomic Energy Agency, Vienna, 1969, 183.

Preston, A. and Mitchell, N. T., Evaluation of public radiation exposure from the controlled marine disposal of radioactive waste (with special reference to the United Kingdom), in Radioactive Contamination of the Marine Environment, Publ. STI/PUB/313, International Atomic Energy Agency, Vienna, 1973, 575.

Pullum, P. A. and Erbisch, F. H., Effects of gamma radiation on the lichen *Cladonia verticillata* (Hoffm.) Schaer, *Bryologist*, 75(1), 48, 1972.

Purdom, C. E., Radiation-induced gynogenesis and androgenesis in fish, *Heredity*, 24(3), 431, 1969, plus 1 plate.

Ragsdale, H. L. and Rhoads, W. A., Four-year post-exposure assay of vegetation surrounding Project Pinstripe: demonstration of the utility of delayed damage appraisals, *Radiat. Bot.*, 14(4), 229, 1974.

Reichle, D. E., Witherspoon, J. P., Mitchell, M. J., and Styron, C. E., Effects of beta-gamma radiation of earthworms under simulated-fallout conditions, in Survival of Food Crops and Livestock in the Event of Nuclear War, *(AEC Symp. Ser. 24)*, U.S. AEC Rep. CONF-700909, Benson, D. W. and Sparrow, A. H., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1971, 527.

Robiller, F. and Unverricht, A., Radiation dose and radioprotective effect in the examination of the thyroid gland of birds, *Radiobiol. Radiother.*, 13(3), 393, 1972.

Sacher, G. A., Ed., Radiation Effects on Natural Populations, Division of Biology and Medical Research, Argonne National Laboratory, Illinois, 1965.

Sankaranarayanan, K., Ionizing radiations, genetic loads, and population fitness: a review, *Arch. Genet.*, 46(3), 137, 1973.

Schultz, V. and Whicker, F. W., Nuclear fuel cycle, ionizing radiation, and effects on biota of the natural environment, *Crit. Rev. Environ. Control*, 10(3), 225, 1980.

Schultz, V. and Whicker, F. W., Nuclear explosives, ionizing radiation, and effects on the biota of the natural environment, in *Management of the Environment*, Patel, B., Ed., Wiley (Eastern), New Delhi, India, 1980, 51.

Soliman, M. H., Lethality: dependence on developmental rate in x-irradiated pupae of *Tribolium*, *Experientia*, 29(5), 550, 1973.

Sparrow, A. H., Schwemmer, S. S., and Bottino, P. J., The effects of external gamma radiation from radioactive fallout on plants with special reference to crop production, *Radiat. Bot.*, 11(2), 85, 1971.

Sparrow, A. H., Schwemmer, S. S., Klug, E. E., and Puglielli, L., Woody plants: changes in survival in response to long-term (8 years) chronic gamma irradiation, *Science*, 169(3950), 1082, 1970.

Stannard, J. N., Toxicology of radionuclides, *Annu. Rev. Pharmacol.*, 13, 325, 1973.

Teresi, J. D. and Newcombe, C. L., An Estimate of the Effects of Fallout Beta Radiation on Insects and Associated Invertebrates, Rep. USNRDL-TR-982, U.S. Naval Radiological Defense Laboratory, San Francisco, Calif., 1966.

Tikhomirov, F. A. and Aleksakhin, R. M., Effect of ionizing radiation on forest biogeocenoses (in Russian), in *Contemporary Problems of Radiobiology*, Vol. 2, Klechovskiy, V. M., Polikarpov, G. G., and Aleksakhin, R. M., Eds., Atomizdat, Moscow, 1971, 228; English transl., *Radioecology*, Greenberg, D., Ed., John Wiley & Sons, New York, 1973, 197.

Underbrink, A. G., Sparrow, A. H., and Pond, V., Chromosomes and cellular radiosensitivity. II. Use of interrelationships among chromosome volume, nucleotide content and D_o of 120 diverse organisms in predicting radiosensitivity, *Radiat. Bot.*, 8(3), 205, 1968.

Williams, R. B., Carmon, J. L., and Smith, M. H., Influence of temperature on the susceptibility of the old-field mouse *(Peromyscus polionotus)* to acute radiation, *Radiat. Res.*, 35(3), 709, 1968.

Willis, D. L. and Lappenbusch, W. L., The radiosensitivity of the rough-skinned newt *(Taricha granulosa)*, in *Radioecology and Energy Resources*, Cushing, C. E., Jr. et al., Eds., Dowden, Hutchinson & Ross, Stroudsburg, Pa., 1976, 363.

Witherspoon, J. P., Radiosensitivity of forest tree species to acute fast neutron radiation, in Symposium on Radioecology, U.S. AEC Rep. CONF-670503, Nelson, D. J. and Evans, F. C., Eds., U.S. Atomic Energy Commission, Washington, D.C., 1969, 120.

Woodwell, G. M., Table 40. Sensitivity to ionizing radiation: major ecosystems and dominant plant species, in *Environmental Biology*, Altman, P. L. and Dittmer, D. S., Eds., American Society for Experimental Biology, Bethesda, Md., 1966, 181.

Zavitkovski, J., Effects of gamma radiation on vegetative and reproductive phenology of herbaceous species of northern deciduous forests, in The Enterprise, Wisconsin Radiation Forest: Radioecological Studies, U.S. ERDA Rep. TID-26113-P2, Zavitkovski, J., Ed., U.S. Energy Research and Development Administration, Washington, D.C., 1977, 127.

Chapter 3

CONSEQUENCES OF RADIOACTIVITY IN THE ENVIRONMENT

I. INTRODUCTION

It is often said that more is known about the consequences of radiation in the environment than of any other form of pollution that may cause harmful effects in man or other organisms. The authors believe this statement to be generally true. Indeed, there has been a vast amount of research on the biological effects of radiation over the past several decades. Some of this effort has been prompted by medical uses of radioisotopes and radiation, but much research is basically motivated by public fear of this tasteless, odorless, invisible and silent form of energy which is generally perceived to produce insidious to complete damage to all living things. Despite the tremendous array and volume of monetary and intellectual resources that have been engaged in problems of radiobiology and radioecology, periodic nuclear accidents, small but highly publicized mishaps, and the specter of nuclear confrontation between nations continues to nurture an attitude of fear among the public about the dangers of radiation. In addition to this attitude of fear, a feeling of uncertainty and doubt has developed as a result of conflicting opinions within the scientific community about risks of low-level radiation. Further, confrontations between the pronuclear establishment and antinuclear activists has bred a milieu of general confusion and mistrust.

While we certainly do understand a great deal about the dangers of radiation, there remain some valid uncertainties about the environmental transport and effects of radioactive material, and some real doubts that human beings will ever have the capability to manage nuclear technologies without mistake, without some finite risk to the public. A large array of factors, many of which are not well quantified, can alter the radiation dose received by people and other organisms from radioactive material released to the environment. Because of statistical uncertainties and experimental limitations, probabilistic occurrences of cancer, genetic defects, and aging from exposure to low levels of radiation are not directly determinable, rather they must be inferred from data at higher dose levels. If someone develops cancer, it is seldom possible to prove the causal factor or factors because many things in addition to radiation can produce cancer. By their very nature, humans are fallible, and by logical extension, so are some of their ideas, materials, and operations. It is foolish to believe that one can live in an error-free, risk-free environment. On the other hand, the premise that one can strive to minimize error and risk is entirely reasonable, provided one is willing to pay the cost to do so.

The generally anthropocentric position of modern man has a definite bearing on the way that radiation dangers are viewed. Important also, is the widely prevailing ethic which centers on the health and vitality of the individual person, rather than on the population as a functional unit. These moral attitudes have produced a very stringent array of radiation exposure standards which are designed to minimize risks to individuals, even though much higher radiation exposures could be tolerated by populations and systems of interacting populations called communities. If the linear dose-response concept is accepted then any dose, however low, produces some finite increment in the risk of deleterious health effects. Since people do not wish to accept additional risk, however low, especially if such risk applies to themselves or to loved ones, it is not difficult to understand the antinuclear sentiment which is so prevalent. On the other hand, mankind, by virtue of sheer numbers and present standard of living, does not really have the luxury of shutting off the nuclear energy option, because to do so

simply increases other risks, many of which are as unthinkable as the prospect of possibly having one's health affected by radiation.

Motivation to write this chapter developed in two ways. First, the earlier chapters discussed the technical matters of how radionuclides are transported in the environment and what sorts of ecological or biological effects can be expected from various levels of exposure to radiation. Although these chapters laid at least part of the necessary foundation, they did not speak directly to the question of the consequences of the present radiation environment or that which could develop in the event of accidents or nuclear warfare. Secondly, the authors feel a moral obligation to interpret scientific fact in their field and relate it to the best of their ability to social concerns. It is done with the realization that their interpretations may be criticized, and some may be wrong; nevertheless, they are willing to accept that responsibility. This chapter is organized on the basis of the consequences of environmental radiation from natural background, routine anthropogenic releases, accidental releases, and nuclear war, as the authors presently perceive them.

II. NATURAL BACKGROUND RADIOACTIVITY

In Volume 1, Chapter 4 the various sources of naturally occurring radiation were discussed. However, little has been said thus far about the relationship of natural radiation, primarily cosmic rays and that from primordial uranium, thorium, and potassium, to life processes. Ordinarily, background radiation is dismissed as a concern to the health of man and the environment because it has always been ubiquitously present and there is little that one could feasibly do to escape it. Life and life-processes have evolved in a radiation environment and there is obvious evidence throughout the biosphere that populations of organisms prosper richly in spite of continual bombardment by ionizing rays and particles. This suggests that although occasional cellular and subcellular damage is no douht caused by the background radiation, organisms have evolved inherent structures and mechanisms which can deal with such damage. It is now known that molecular repair and cellular replication are two such mechanisms. In addition, the process of natural selection, both at the cell population and the organism population levels, operates in such a way as to eliminate damaged or otherwise unfit biological material. Because of such mechanisms, we find little, if any, solid evidence that the geographic variations in natural background radiation cause significant effects in living populations, and we commonly use background radiation as a yardstick with which to judge the hazards of anthropogenic radiation.[1]

Despite the apparent insignificance of natural background radiation in our daily lives, there is more to the story, especially if we consider some major geophysical processes of importance to life and also if we look back in time to the basic origins and evolution of life. A most basic fact is that our biosphere is essentially nuclear powered. The carbon cycle, starting with photosynthesis, requires energy from the sun in the form of certain wavelengths of visible light. The infrared from the sun is also important to the heating of the environment and the speeding up of critical biochemical reactions. Solar heat and light emanates continuously from the gigantic furnace nearly 92 million miles from earth. This furnace is hydrogen powered from the same basic nuclear fusion reactions that man has learned to produce for nuclear explosives, but has not yet been able to contain to provide supplemental energy.

Another fact is that most of the heat generated within the earth is produced by the decay of primordial radionuclides in the earth.[2] Nearly all the decay energy of radionuclides in the earth is degraded to heat. Based on the average crustal content of natural uranium, thorium, and potassium, a simple calculation shows that about 10^{-11} cal/min are produced in a gram of earth. With the knowledge that the earth weighs

about 6×10^{27} g, and the assumption (not necessarily correct) that the average radionuclide content of the earth is the same as that of the surface crust, an order of 6×10^{16} cal/min are generated within our planet. Actually, this is considerably more heat (∼196 μcal/cm²-sec) than is known to be flowing up out of the earth (1.5 μcal/cm²-sec) and it is thus inferred that most of the primordial radioactivity is confined to the crustal zone. Were it not for this radioactivity, the average temperature of the ground would be significantly lower, and major geophysical processes would be altered.

Just a few years ago, Dr. Follin of The Johns Hopkins University postulated on the basis of his research that without cosmic rays there would probably be no lightning.[3] His theory is that thunderheads would not have the electrical potential necessary to initiate a lightning bolt without the ionization produced within the cloud by cosmic rays. Ions produced by cosmic rays are possibly accelerated by the electric field already existing within the cloud, causing sufficient buildup of negative charges at the bottom of the cloud to initiate a lightning stroke. Strokes may then travel toward the earth along paths of ionization created by the passage of secondary cosmic rays, mostly muons. This leader stroke is met near the ground by an electric discharge which leaps up from the earth, completing the circuit and establishing a pathway for a powerful return stroke from the ground to the cloud. Lightning and cosmic rays are probably significant factors in the conversion of inert nitrogen gas in the atmosphere to oxidized forms which can be used by plants and animals.[4]

Now that the authors have briefly considered the impact of natural radiation and radioactivity on some geophysical processes of critical importance to life as it is known, they will next examine the direct impact of background radiation on the life process. Although natural radiation appears to have little, if any, obvious impact on organisms in the short-term, there is evidence that it has possibly affected the process of biological evolution. This influence, though subtle, has been steadily maintained from the earliest beginnings of life. In fact, the story of biological evolution must be preceded by chemical evolution, the creation of organic compounds from the simple elemental constituents carbon, hydrogen, nitrogen, and oxygen.

A substantial amount of work has been done to understand the creation and evolution of life,[5] and numerous investigations have centered on the influence of ionizing radiation on the synthesis of biologically significant compounds which must have preceded the first life forms.[6-8] Various studies have shown that it is possible to produce biologically important compounds by exposing presumed constituents of the earth's primordial, reducing atmosphere, such as ammonia, methane, and water vapor, to ionizing radiation. Compounds produced in the laboratory by this means include amino acids, the building blocks of proteins; purines, pyrimidines, ribose, and deoxyribose, all constituents of deoxyribonucleic acid; and the adenosine phosphates.[7] However, other forms of energy present on the primitive earth, such as ultraviolet light, electrical discharges, and heat (volcanoes) can also produce such abiogenic chemical conversions, and these energy sources were likely much more abundant overall than cosmic rays or terrestrial radioactivity.[6] On the other hand, it is entirely possible that geologic concentrations of terrestrial radioactivity, as well as significant temporary increases in cosmic ray flux during postulated magnetic field polarity reversals, could have substantially increased the relative importance of ionizing radiation at selected points in time and space.

Subsequent to the abiotic formation of amino acids, and other classes of organic compounds, chemical evolution toward primitive life forms must have involved polymerization reactions and production of protein-like material. Such primitive proteins or "proteinoids" have been produced in the laboratory by abiotic means.[8] In fact, such proteinoids can form microspheres having properties similar to biological cells, including a high degree of stability in aqueous suspension. The role of ionizing radia-

tion in the formation of high molecular weight biopolymers does not presently seem clear because of the other energy sources available and because both synthesis and decomposition can result; depending upon the compounds involved, the dose rate, and the chemical environment. Based upon laboratory work and the wide range of plausible physical and chemical environments of the prebiotic earth, the opportunities for the evolution of organic compounds and polymers could have been almost limitless.

Let us next turn to the problem of the evolution of living organisms, and the possible role of natural background radiation. Evolution, the change in form and function of organisms over time, is the result of natural selection acting upon varied individuals. Thus evolution has two principal driving forces, variation and selection. Variation among individuals is largely the result of variation in genetic constitution. Changes in genetic constitution may be produced by gene mutations, which in turn may be produced by ionization radiation, mutagenic chemicals, heat, and other factors. The question of significance at this point is: what is the influence of ionizing radiation on the evolution of the species, including man?

According to Crow:[9] "...it is likely that ionizing radiation has played only a minor role in the recent evolutionary history of most organisms," and, "as for the earliest stages of evolution, starting with the origin of life, it is problematical whether ionizing radiation played a significant role even then." Much of the evidence as to the relative insignificance of ionizing radiation in producing gene mutations comes from work with short-lived species such as the fruit fly, *Drosophila*. Although it was clearly demonstrated that ionizing radiation causes the same kinds of mutations which occur spontaneously, the frequency of mutation from natural background radiation levels would be insignificant in comparison to the spontaneous mutation frequency. Natural radiation would have to be increased by some four orders of magnitude to account for the spontaneous mutation rate in *Drosophila*. However, if a spectrum of other organisms is considered, it is observed that the relative importance of natural ionizing radiation in producing mutations increases with reproductive life span. In very long-lived species, it is even possible that the majority of mutations are produced by radiation. In man, roughly 15% of the natural mutation frequency may be accounted for by background radiation, if a doubling dose of 20 rem and a linear dose-mutation frequency curve is assumed.[1]

What then, are the consequences of gene mutations, irrespective of their cause? There is overwhelming evidence that the vast majority of mutations are harmful to individuals that possess them and the tendency is for natural selection to eliminate such deleterious genetic information from the population.[10] While this is usually beneficial to the population, it is tragic to the individual. There is some chance that mutations will be beneficial, that is, they may lead to improved fitness, survival or reproduction, but this chance is usually quite small. However, it is precisely this kind of chance occurrence that can bring about evolutionary change in populations. Such evolutionary change not only requires individual variation; it also requires changes in selection criteria based on alterations in the environment over time or space. The rapidity of evolutionary change is governed by the rate at which the environment changes, as well as by the amount of individual variation. If a population is genetically homogeneous and the environment changes rapidly in comparison to reproductive life span, extinction is more likely than evolution. On the other hand, evolution of genetically diverse, highly reproductive species can usually keep pace with even quite rapid environmental changes.

In summary, there is no doubt that the natural radiation background is an integral and in fact, necessary, part of our present environment. It is linked to many geophysical processes that are of critical importance to life, and has played some, though quantitatively uncertain, role in the origin and evolution of living organisms. Changes

in the ionizing radiation environment of the same order-of-magnitude as present geographic variations in natural background are not expected to cause observable or even subtle harm to populations. On the other hand, ionizing radiations at natural background intensities may produce some fraction (probably a very low fraction) of the imperfections in health and function of individual cells and organisms.

III. ROUTINE ANTHROPOGENIC RELEASES OF RADIOACTIVITY

Whether we like it or not, radiation and radioactivity are very much a part of advanced human societies, and the trend is toward more intensive use of nuclear energy with time. The uses of nuclear energy have tangible benefits to society in such diverse areas as electric power generation, medicine, industry, and agriculture. The basic causes of the increased utilization of nuclear energy are increasing human populations, a shrinking supply of natural resources, and technological advancements. Societal symptoms resulting from these basic changes are increased health risks, increased awareness and concern about such risks, increasing regulation to minimize such risks, and increased monetary outlay to satisfy such regulation.

Since it seems to be human nature to grapple with these symptoms rather than to face up to their root causes, let us consider the consequences of man's uses of nuclear energy. In this section, the authors will examine the routine environmental releases of radioactivity that are the generally unavoidable result of nuclear energy utilization. Here, they will clarify their use of the term "unavoidable." Actually, zero releases might be technically achievable, but the cost of attaining this is likely to be so high as to preclude the particular application in the first place. Thus, if nuclear energy is to be used feasibly, some finite release is usually "unavoidable."

Probably the most significant and widespread routine releases of anthropogenic radioactivity to the environment will result from operations within the nuclear fuel cycle (Volume I, Chapter 4, Tables 10 through 13). However, other releases such as those from national defense installations, hospitals, research laboratories, and industry must not be neglected. The determination of radionuclide discharge limits from various facilities is a rather complex matter, involving national committees, state and federal agencies, and the enactment of state and federal laws. The usual line of logic is the determination of permissible radiation dose limits (by committee recommedations and enactment into law), and the determination of discharge limits which could result in the achievement of permissible dose. The latter must account for dispersion, inhalation, external exposure, and food chain transport.

Over the past several decades, and in fact dating back to the late 1920s, a number of committees and formal organizations have evolved to deal with the question of setting standards for radiation protection of man. A historical review of this development has been compiled by Taylor.[11] At present, two committees are most significant and influential; the National Council on Radiation Protection and Measurements (NCRP) and the International Commission on Radiological Protection (ICRP). These committees, composed of scientific experts on radiation hazards, recommend dose limits for radiation workers and other members of the human population. Such recommendations, after being subjected to debate and public hearing, may be enacted into law. Title 10, Part 20 of the Code of Federal Regulations (10 CFR 20) specifies legal dose limits for various segments of the human population. Generally, familiar dose limit values of 5 rem in any 1 year for occupationally exposed individuals and 0.5 rem in any 1 year for other members of the population are specified in 10 CFR 20.

It is the general responsibility of the U.S. Environmental Protection Agency (EPA) to assure that installations keep radioactive discharges low enough that the concentrations in air and water at the boundary of such installations are sufficiently low so as

to assure that dose limits to nonoccupationally exposed individuals are not exceeded. The working dose limit utilized by EPA is only 25 mrem/year to the whole body (40 CFR 190). The regulation of radiation within the property boundaries of installations that handle radioactive material is the responsibility either of the U.S. Nuclear Regulatory Commission (NRC) or the individual state, depending on which agency is responsible for licensing. At present, some 25 states, called "Agreement States", are responsible for their own licensing programs, while NRC maintains regulatory authority in the remaining states.

The radiation dose limits which are written into law are intended as guides for maximum allowable exposures. In actual practice, it is generally recognized that societal needs can be achieved with far lower average doses to the population. Out of this fact, and the prevailing desire to reduce health hazard risks as much as possible, a philosophy of "as low as reasonably achievable (ALARA)" has developed. Under this philosophy, installations that release radioactivity are expected to mimimize discharges to the extent that is feasibly possible within the prevailing technological and economic constraints.

It should be noticed that our discussion of radiation protection philosophies and standards has centered on the protection of humans. Yet this book has been concerned with the environment in the broad sense, with all living organisms being of interest. How then, can these two apparently different matters of concern be reconciled? While we have carefully developed stringent protection standards for mankind, we have no such comparable standards for other species exposed to radiation through anthropogenic releases to the environment. Since human health and welfare is closely tied to the quality of the environment (which includes all other living things), shouldn't we also be concerned with radiation protection standards for other species?

A number of years ago, the authors felt that indeed, some effort should be devoted to the development of radiation protection standards for other species. The data on radionuclide levels clearly indicated higher concentrations, and thus higher dose rates, in many wild organisms than in humans. This finding would be expected on the basis of protection afforded humans by food chain barriers and the washing and preparation of many dietary items. In addition, humans would know about, and thus avoid, locally contaminated areas, while other species would not have any such means of spatial discrimination.

After further consideration of the problem however, the authors conclude that the radiation protection standards based on human risk are so stringent that other species will be adequately protected by adherence to such standards. While individuals of nonhuman populations may receive somewhat higher radiation exposures than humans from routine environmental releases, selection processes will prevent deleterious population changes at the exposure levels anticipated or already experienced. The facts that reproductive life spans of most species are considerably shorter than those of humans, and that performance is generally measured at the population level in nonhuman species, strengthen this position. Searches for deleterious effects of radiation in plants and animals occupying areas much more heavily contaminated than those receiving routine effluents at permissible levels have been generally negative. The exceptions are areas exposed accidentally or by experiment to extremely high levels of radioactivity.

Given then, that routine anthropogenic releases of radioactivity are controlled to the extent that regulatory standards and guidelines are not exceeded, deleterious effects in nonhuman populations will not be evident, and the risk to humans should be acceptably low. Of course, what risk is "acceptable" is a matter of social judgement. However, considering the health risks from nonnuclear technologies that are willingly accepted by society,[12] the risks from routine releases from nuclear technologies will be comparatively low when balanced against societal needs and benefits.

IV. ACCIDENTAL RELEASES OF RADIOACTIVITY

Perhaps as fundamental as the law of gravity is the one which simply says: "human beings make mistakes." Who could possibly question that people are fallible in moral character, knowledge, judgement, and execution. Since people are fallible, so must be their creations. Since nuclear technology is a human creation, it must be fallible. An eloquent treatise of this very subject was presented a few years ago by Hardin,[13] who concluded with the hope that if one is destined to have a major nuclear accident, may one have it soon, so as to possibly avoid the problems of "atomic addiction". Hardin's feeling that while the nonhuman links in the chain leading to atomic energy can be improved by technology, very little can be done to improve the human links, is shared by the authors. Even by redundancy in safety systems and the minimization of "human links", the authors do not see how the human factor can be factored out of the nuclear technology equation.

Given that people are subject to human error and inadequacy, and that people control nuclear technology, occasional accidents are inevitable. The frequency of such accidents can be expected to increase as the utilization of nuclear technology increases, unless the rate of safety improvement exceeds the rate of growth in utilization. The magnitude of possible accidents tends to be related inversely to the probability that they will occur. For example, the probability that a technician will drop and break a container of radioactive liquid is very high, but the consequences of this are very low. At the other extreme, the consequences of a reactor core meltdown and major breach of containment could be great, but the probability of such an occurrence is low. Obviously, the effort and money spent to minimize the risk of an accident is related to the consequences of the accident, should it occur.

Accidents are very much a part of society and even of our individual daily lives. Automobiles and airplanes kill thousands of people every year and yet most people still accept the risk of death or serious injury to get conveniently from one place to another. Refinery workers risk explosions and miners risk cave-ins to bring home a good paycheck. It is difficult to think of any day to day activity that is completely risk free. Many risks have consequences that are of the same order of magnitude as a major nuclear accident, such as massive refinery explosions, toxic chemical spillages, dam breaks, and massive air pollution episodes.[12] Such accidents, under certain yet foreseeable conditions, could kill hundreds to thousands of people.

Nuclear accidents are usually so highly and spectacularly publicized that the public develops a disproportionate fear of nuclear vs. other accidents. A good case in point is the Three Mile Island reactor accident in 1979. This accident involved a cooling malfunction that resulted in a super-heated core and concern for an uncontrolled meltdown. This reactor is located in a heavily populated area near Harrisburg, Pa. The publicity was so intense, and so confusing, that many people living even several hundred miles away considered evacuation. Fortunately, workers were successful in eventually cooling the reactor core and effectively controlling the release of dangerous quantities of radioactivity.

While the Three Mile Island accident did not cause identifiable damage from radioactivity to people or other life around the plant, it clearly demonstrated that major, potentially catastrophic nuclear accidents are possible, despite the seemingly foolproof safety systems inherent in modern reactors. This accident was considered by many to be a major setback for the growth of nuclear power. In all likelihood however, this incident will not stop nuclear power, but it probably will lead to improvements in design, regulation, operator vigilance, and future reactor siting.

A reactor core meltdown is not the only conceivable kind of nuclear accident having potential for releases of radioactivity to the environment in sufficient quantities to

cause serious damage to human health and to nearby ecosystems. For example, evidence has only recently come to general attention that an accident of major proportions involving stored nuclear wastes occurred in Russia in 1957 or 1958. The former Soviet scientist, Medvedev, now living in exile, is largely responsible for bringing this event into the open. After years of secrecy and suppression by the Soviets and apparently also by the U.S. Central Intelligence Agency, Medvedev published two articles in 1976 and 1977 about the disaster.[14,15] In 1979 he published a book, giving more details on the event.[16] Very recently, scientists at Oak Ridge National Laboratory published a detailed analysis of the accident.[17]

The site of the accident was reportedly in the southern part of the Ural mountains between the cities of Chelyabinsk and Sverdlovsk, near the smaller city of Kasli. Based on a rather fascinating array of evidence, most of which was indirect, Medvedev concluded that a large explosion involving stored concentrated wastes from military reactors occurred and that large quantities of fission products were dispersed over an area of approximately 800 to 1200 mi^2. The accounts of Medvedev indicate that the levels of radioactivity were so high in many areas that entire villages were evacuated and abandoned. Large numbers of people were treated for radiation sickness, and probably many died as a result of the contamination.

Much of the evidence for this contamination event was the publication of numerous articles in the Soviet literature.[17] These articles dealt with radioecological concentration patterns of moderately long-lived fission products, especially ^{90}Sr and ^{137}Cs, in water, soil, and native biota. Of specific note was the mention of lakes up to 11 km^2 containing (by crude calculation) perhaps 50 kCi ^{90}Sr and land areas containing up to 3 mCi $^{90}Sr/m^2$. Based on computations by Trabalka and colleagues at Oak Ridge National Laboratory an area of some 100 to 1000 km^2 was sufficiently contaminated to cause evacuation of human residents, and such an area was estimated to contain roughly 10^6 Ci of ^{90}Sr.[17] While there is indication that the literature published in connection with the contaminated area was carefully screened so as not to reveal the exact location of the studies and source of the radioactivity, some articles clearly suggest that large areas of landscape were contaminated, and with much greater amounts of radioactivity than would be needed to simply study the behavior of the material. The species studied, and the ecological descriptions of study areas match closely with what would be expected in the Chelyabinsk region.

It is unlikely that the full truth of the Urals disaster will ever be revealed, and there are some possible alternatives to Medvedev's conclusions.[18] However, should Medvedev's arguments be correct, as they appear to be, then one has a classic example of a nuclear accident of major proportions and consequences involving stored wastes. Certainly, it is well known that the quantities of stored nuclear waste, when measured in terms of activity, are very large. Should something, however unlikely, occur that would release a significant fraction to the environment over a short time period, then dramatic ecological effects and serious human health hazards are conceivable.

Another kind of accident that can be cited is a uranium mill tailings dam failure. Several such failures have occurred, and rather large quantities of radioactive progeny of natural uranium, such as ^{230}Th, ^{226}Ra, and ^{210}Pb have been released to local environs. Because the radioactivity in tailings is contained in a very large volume of solid material, the radioactivity is not sufficiently concentrated to produce the same sorts of effects that could occur from the release of stored reactor wastes or nuclear fuel elements. Nevertheless, a tailings dam break is possibly serious enough, depending on the locality and ecological factors, to warrant expensive cleanup measures and avoidance of the contaminated area.

Other possibilities for nuclear accidents could be discussed, such as transportation mishaps, industrial fires or explosions, and crashes of nuclear-armed bombers or nu-

clear-powered vessels. Depending on the inventory of radioactive material and the quantity released in any type of accident, biological and ecological effects are conceivable. However, the area so affected is likely to be more or less limited in size, depending on the quantity of activity released and the pattern of dispersal. If one consider the largest spot inventories of radioactive materials, such as those that might be found at weapons plants, large reactors, and high level waste storage facilities, the most catastrophic event conceivable could seriously contaminate areas of perhaps tens to hundreds of square miles. Of course, the overall risk factor for such an event is the product of a probability factor and a consequence factor. While the probability factor can be engineered to be extremely low, no one is likely to convince us that it can be lowered to zero.

V. NUCLEAR WARFARE

The prospect of a major exchange of nuclear weapons between nations is so terrifying, and the implications so complex, that to most the scenario becomes almost unthinkable. This is probably why the authors have put this topic off to the end of the book. It is easier not to think such painful thoughts, especially as one observes world tensions and the underlying quest for the earth's shrinking resources. It is much easier to escape into our immediate, relatively comfortable surroundings and focus on the more pleasant aspects of life.

Sadly, ever since the devastation of Hiroshima and Nagasaki, a grim arms race has been proceeding within the borders of the major nuclear powers, and now, possibly tens of thousands of nuclear warheads are poised for instant use. The nuclear arms inventory is so great, that the use of even a small fraction of that inventory could produce damage far beyond any human experience. There are those who have argued, perhaps correctly, that security requires strength. Perhaps nuclear capability, and the fear of nuclear retaliation, has prevented the cold war from becoming a hot one. However, one can only wonder how long this situation can last. Possibly, the world political boiler is like the steam variety, needing small, periodic steam releases to prevent such a buildup of pressure that a catastrophic rupture occurs. Using this analogy, the growing population, finite natural resources, and an expanding nuclear arsenal would seem to be increasing political pressure to that uncertain point in time when the pressure can no longer be contained.

The seriousness of the prospect of nuclear war can be qualitatively visualized by a very simple equation: G = RC, where G = the gravity factor, R = the risk factor, and C = the consequence factor. In reality, the risk and consequence factors are very difficult to evaluate in quantitative terms. However, the following qualitative relationships are simple and straightforward. For the risk factor

$$R \propto \left(\frac{\text{population size} \times \text{per capita resource use}}{\text{resource inventory}}\right)$$

which simply says that the risk factor is proportional to population size and per capita consumption, and inversely proportional to the resource inventory. For the consequence factor, we propose,

$$C \propto (\text{nuclear warhead inventory} \times \text{inventory fraction deployed})$$

which suggests that the consequences of nuclear war will increase in proportion to the nuclear inventory and the fraction of that inventory used. Of course, the warhead

inventory is the product of the production rate and time, suggesting that unless production is halted, the inventory and hence the consequence factor will continue to increase with time. While these relationships are highly oversimplified, they capture the essence of the problem. Also these relationships clearly indicate how the world could go about the task of reducing G, the gravity of nuclear warfare.

Beyond the simple relationship suggested above, the authors claim no ability to suggest how the risk factor might be evaluated. To do so would involve politics, economics, psychology, military science, and other fields beyond the scope of this book. However, radioecology can make a definite contribution to evaluation of the consequence factor. While a determination of the magnitude of a nuclear exchange is also beyond this subject matter, approximate evaluation of the ecological consequences of a given magnitude of exchange, should it occur, is possible within the present framework of radioecological data.

The ecological effects of a nuclear exchange would result primarily from gross physical damage due to blast and fire, longer-term changes due to biological damage from ionizing radiations, and biological damage from ultraviolet light. The direct physical damage from blast and fire would be apparent immediately after nuclear detonation, but such effects would be confined to the local vicinity of each target. The effects of ionizing radiation could be manifest over a larger geographic area, perhaps of a regional scale, and ecological changes might be evident from days to years following the event, depending on exposure levels. Worldwide effects have been postulated on the basis of a dramatically increased ultraviolet flux, resulting from the destruction of atmospheric ozone by the nitrogen oxides released in the detonations. Stratospheric ozone is normally present in sufficient quantity to absorb most of the ultraviolet (UV) light impinging on the atmosphere and thus acts as a protective shield against its harmful effects.

The physical damage to be expected from the blast and fire of a nuclear detonation can be assessed from a number of studies carried out in conjunction with nuclear testing programs, and from the Hiroshima-Nagasaki experience.[19-22] Miller[21] describes the physical damage that might be expected from a 5 (Mt) land-surface detonation, with the conclusion that within a radius of 5 mi of ground zero, extensive physical damage from blast and fire can result. Within a zone between 5 and 10 mi radius, damage is also expected, primarily from fire. Of course, the precise magnitude and pattern of physical damage is dependent on many factors, including the size of the warhead, the altitude of detonation, and the nature of the land surface. The major factors affecting the ignition of materials and the spreading potential of fires are discussed by Broido.[22]

Of greater concern to the radioecologist are the effects of ionizing radiation from fallout within the regional deposition pattern. Miller[21] prepared a map of the U.S. showing idealized fallout patterns from a hypothetical 20,000 Mt attack, assuming 100% fission yields (Figure 1). The darkest areas represent regions that could receive >10,000 R/hr at 1 hr. The total exposures in R as a function of time can be estimated from the commonly assumed power function relationship describing the decay of mixed fission products. Starting with

$$R(t) = R(1)t^{-1.2} \qquad (1)$$

where R(t) is the exposure rate vs. time t (t in multiples of unit reference time) and R(1) is the exposure rate at unit reference time, one can integrate to obtain:

FIGURE 1. Fallout contour map for a hypothetical 20,000 Mt attack on the U.S. Contours are in R/hr at 1 hr, assuming land-surface detonations with 100% fission yields. (After Miller, C. F., Ecological Effects of Nuclear War, U.S. AEC Rep. BNL-917(C-43), Woodwell, G. M., Ed., Brookhaven National Laboratory, Upton, N.Y., 1965, 1.)

$$R_{integrated} = \int_1^t R(t)dt$$

$$= R(1)\int_1^t t^{-1.2}\,dt$$

$$= 5R(1)\left[1 - t^{-0.2}\right] \qquad (2)$$

After 30 days, for instance, Equation 2 shows that the integrated exposure is 3.66 R(1), which is roughly 73% of the exposure integrated to infinity. Thus, the short-term (30 day) integrated exposures to areas receiving >10,000 R/hr at 1 hr in Figure 1 would be >36 kR. Comparing this value to those in Chapter 2, Table 10 in this volume, it is evident that such exposures would severely damage forest and shrub communities of North America. Some variable damage, depending on exposure and community type, would be expected in other ecosystems as well. Acute exposures >10 kR would cause early mortality in a large array of animal populations (Chapter 2, Figure 4 in this volume).

Using such hypothetical scenarios and the available data, it is clear that nuclear war could cause profound ecological changes over large areas of landscape. However, the quantitative prediction of the pattern and magnitude of ecological change involves so many parameters and uncertainties, that such a task would be formidable. Perhaps it is sufficient to know that dramatic, extensive changes would be induced by such a

catastrophic event, without knowing the finer details. It is unlikely that precise knowledge of such details would affect the probability of having a nuclear exchange.

A recent study by several committees of experts working under the aegis of the National Academy of Sciences (NAS) developed the point that worldwide effects of significance could result from ultraviolet light and possibly global climatic change in the event of a major nuclear war.[23] Such phenomena could impact even those nations not directly involved in a nuclear exchange. Ultraviolet-B exposures, according to the NAS study, could increase as much as 650% during the first year following the detonations. The UV-B flux would diminish thereafter, reaching a value of about 9% above current levels within 3 years. Such worldwide increases in the UV-B flux could produce a high incidence of skin cancer and disabling sunburn in humans exposed for short periods. There is also reason to believe that UV-B, at such levels, could inhibit photosynthesis and thus plant growth, increase mutation rates, affect pollination behavior of insects and kill certain organisms outright.[23] The possibility of climatic change is based largely on loading of the atmosphere with dust particles and the depletion of ozone. Such atmospheric alterations could induce a chain of events involving mean global temperature depressions, wind shifts, and alteration of precipitation patterns, which in turn could have profound effects on natural and managed ecosystems.

Of course, the stresses of blast, fire, ionizing and ultraviolet radiation, and possible climatic change will diminish after a nuclear exchange, and the opportunity for ecological recovery would follow. The educated speculations of Dr. J. N. Wolfe, in testimony before the 86th Congress of the U.S. in 1959, indicated that full ecological recovery would eventually follow a nuclear holocaust.[24] Subsequent study by experts having the benefit of pertinent research findings did not alter the statements of Dr. Wolfe. While ecosystems are certainly vulnerable to short-term damage from the stresses resulting from nuclear detonations, there are no features associated with such stresses that would preclude ultimate recovery.[25] The rate and pattern of ecological recovery can be predicted from principles of ecological succession and pertinent data from field studies.

Although the point is made that eventual ecological recovery following nuclear war is virtually certain, a period of some years' duration, during which severe hardship and social disorder prevails, is likely. Of immediate concern following a nuclear war is the ability of agricultural systems to sustain surviving human populations. A symposium held at Brookhaven National Laboratory in 1970 featured numerous papers dealing with the survival of food crops and livestock in the event of nuclear war.[26] A general conclusion that could be drawn from this meeting is that, depending on the attack scenario, food production capability would be more or less impaired. The magnitude of the problem would be related to the intensity and pattern of the attack, as well as its timing in relation to agricultural practices. The more recent NAS study found that many technical uncertainties preclude an accurate prediction of agricultural effects.[23]

Our conclusion about the prospect of a major nuclear war is that such an event would bring about horror and suffering to a degree far beyond human experience. The dangers of civilian nuclear power and of other nuclear risks facing societies seem virtually imperceptable when compared with the potential danger of nuclear warfare.

VI. SUMMARY

Having just discussed natural background radioactivity, routine and accidental releases of radioactive material, and nuclear warfare, one should be in a position to explore the overall question, "What are the consequences of radioactivity in the environment?" Certainly, it is evident that the question of consequences involves fun-

damental biological responses to the radiation energy absorbed in living tissue. The magnitude and ramifications of the biological response is primarily a function of the amount of energy absorbed, or the rate at which it is absorbed. The rate at which energy is absorbed from natural background radiation is not sufficient to be of general biological concern. This is not so much that no subcellular damage occurs at background radiation levels, for some indeed does occur, but rather it is largely because biological systems have evolved structures and mechanisms that can cope with this persisting stress. Clearly, the intensity of stress from ionizing radiation must be increased substantially above that from natural background before deleterious biological responses are observed. At very high dose levels, one can predict biological effects with considerable certainty. However, at low-dose levels, from say, 1 to 1000 times the background level, the shape of the dose-response curve is uncertain and quantification of biological effect or risk is likewise subject to uncertainty.

It is apparent that dose rates to biological tissues from routine anthropogenic releases will generally be on the same order of natural background or considerably less, provided that established regulations and guidelines are followed. At such doses, population and community level changes are not anticipated, thus ecological effects can be assumed to be unmeasureable. However, there is the possibility of increased risk of cancer, genetic abnormalities, and life-span shortening in exposed individual organisms. This statement, being true for humans as well as other species, brings about resistance to nuclear activities. However, the incremental risk from routine nuclear activities is expected to be very small relative to the inherent, unavoidable risks that all individuals are faced with. Virtually all modern technologies that are assumed to bring benefits to mankind carry definite risks to individuals. In this sense, nuclear power is no different than other technologies, and in fact, the benefit/risk ratio for nuclear power may be higher than for other energy technologies. Let us not overlook the fact for example, that to shut down nuclear power simply increases dependence on foreign oil and increases the risk of nuclear warfare, to say nothing of problems such as inflation and unemployment.

This is not meant to imply that the authors endorse the rapid development of nuclear power. It is more a matter of making difficult choices, i.e., making the best of several partially undesirable ones. It is fully recognized that nuclear power, being inseparably dependent on human factors and the unpredictable forces of nature, is not without risk of catastrophic accidents. However, the same can be said of hydroelectric dams and large oil storage depots. In order to maintain our standard of living and avoid massive human mortality from starvation or war, then it seems that all forms of energy must be developed to keep pace with demand.

Our major, underlying fear though, is the ultimate consequences of the burgeoning human population and the incredible rate at which the natural resources of the earth are being consumed. The earth and its resources are finite, and thus is its ability to support the human population. The basic situation is conceptually as simple as the growth of cells in a petri dish. With ample nutrient media a few healthy cells quickly multiply until the space and/or nutrients are exhausted. Following that, the cells die from malnutrition or from their own poisons. No one really knows how many people the earth can support. However, there are imminent signs now of deteriorating life support systems. Only recently is one beginning to realize how much nature's services are really worth to human welfare.[27] Starvation is common in many areas of the world. Will deforestation and the burning of fossil fuels trigger global climatic changes through modification of the carbon dioxide cycle?[28] Why do nations war with one another? Differences in ideologies, religious beliefs, and political positions are sometimes merely excuses to war over the more fundamental needs of natural resources, such as space, land, waterways and other things needed to accommodate human population growth and a [illegible] standard of living (or expectation).

If the growth of population and per capita resource consumption cannot be consciously controlled and eventually stabilized, then disastrous consequences appear to be the only plausible scenario. Whether the release of human pressure will be accomplished by nuclear, chemical, biological or other means cannot be predicted. Certainly, virtually all credible scenarios for the future of mankind and his support systems, be they optimistic or pessimistic, will involve nuclear energy in one form or another.

A thorough understanding of human nature, natural resource ecology, and nuclear energy is clearly essential if mankind is to shape his own destiny.

REFERENCES

1. Advisory Committee on the Biological Effects of Ionizing Radiations, The Effects on Populations of Exposure to Low Levels of Ionizing Radiation, National Academy of Sciences-National Research Council, Washington, D.C., 1972.
2. **Longwell, C. R. and Flint, R. F.,** *Introduction to Physical Geology,* John Wiley & Sons, New York, 1955.
3. **Sullivan, W.,** Scientists believe cosmic rays generate electricity that causes a stroke of lightning, *New York Times,* p. 38, December 8, 1977.
4. **Delwiche, C. C.,** The nitrogen cycle, *Sci. Am.,* 223(3), 137, 1970.
5. **Oparin, A. I.,** *The Origin of Life on Earth,* 3rd ed., Oliver & Boyd, Edinburgh, 1957. (English transl. by A. Synge.)
6. **Miller, S. L. and Urey, H. C.,** Organic compound synthesis on the primitive earth, *Science,* 130(3370), 245, 1959.
7. **Ponnamperuma, C.,** The role of radiation in primordial organic synthesis, in *Radiation Research,* Silini, G., Ed., North-Holland, Amsterdam, 1967, 700.
8. **Fox, S. W.,** Radiation and the first biopolymers, in *Radiation Research,* Silini, G., Ed., North-Holland, Amsterdam, 1967, 714.
9. **Crow, J. F.,** Ionizing radiation and evolution, *Sci. Am.,* 201(3), 138, 1959.
10. **Wallace, B. and Dobzhansky, Th.,** *Radiation, Genes, and Man,* Henry Holt, New York, 1959.
11. **Taylor, L. S.,** *Radiation Protection Standards,* CRC Press, Boca Raton, Fla., 1971.
12. **Beckmann, P.,** *The Health Hazards of Not Going Nuclear,* Golem Press, Boulder, Colo., 1976.
13. **Hardin, G.,** Probable results of atomic energy dependency, in *Radioecology and Energy Resources,* Cushing, C. E., Jr., et al., Eds., Dowden, Hutchinson & Ross, Stroudsburg, Pa., 1976, xvi.
14. **Medvedev, Z.,** Two decades of dissidence, *New Sci.,* 72(1025), 264, 1976.
15. **Medvedev, Z.,** Facts behind the Soviet nuclear disaster, *New Sci.,* 74(1058), 761, 1977.
16. **Medvedev, Z. A.,** *Nuclear Disaster in the Urals,* W. W. Norton, New York, 1979.
17. **Trabalka, J. R., Eyman, L. D., and Auerbach, S. I.,** Analysis of the 1957-58 Soviet Nuclear Accident, U.S. DOE Rep. ORNL-5613, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1979.
18. **Stratton, W., Stillman, D., Barr, S., and Agnew, H.,** Are portions of the Urals really contaminated?, *Science,* 206(4417), 423, 1979.
19. **Glasstone, S. and Dolan, P. J.,** The Effects of Nuclear Weapons, 3rd ed., Department of Defense, U.S. Department of Energy, Washington, D.C., 1977.
20. **White, C. S.,** Biological Effects of Blast, Rep. DASA 1271, Tech. Prog. Rep., Lovelace Foundation for Medical Education and Research, Albuquerque, N.M., 1961.
21. **Miller, C. F.,** Physical damage from nuclear explosions, in Ecological Effects of Nuclear War, U.S. AEC Rep. BNL-917(C-43), Woodwell, G. M., Ed., Brookhaven National Laboratory, Upton, N.Y., 1965, 1.
22. **Broido, A.,** Effects of fire on major ecosystems, in Ecological Effects of Nuclear War, U.S. AEC Rep. BNL-917(C-43), Woodwell, G. M., Ed., Brookhaven, National Laboratory, Upton, N.Y., 1965, 11.
23. Assembly of Mathematical and Physical Sciences, *Long-Term Worldwide Effects of Multiple Nuclear — Weapons Detonations,* National Research Council, National Academy of Sciences, Washington, D.C., 1975.
24. **Wolfe, J. N.,** Longtime ecological effects of nuclear war, in Biological and Environmental Effects of Nuclear War, Hearings before the Special Subcommittee, June 22 to 26, 1959, Joint Committee on Atomic Energy, U.S. Congress, U.S. Government Printing Office, Washington, D.C., 1959, 832; U.S. AEC Rep. TID-5561, U.S. Atomic Energy Commission, Washington, D.C., 1959.

BEST AVAILABLE COPY

25. Committee of the National Academy of Sciences, Civil Defense: Little Harbor Report, U.S. AEC Rep. TID-24690, U.S. Atomic Energy Commission, Washington, D.C., 1969.
26. **Bensen, D. W. and Sparrow, A. H., Eds.**, Survival of Food Crops and Livestock in the Event of Nuclear War (AEC Symp. Ser. 24), U.S. AEC Rep. CONF-700909, U.S. Atomic Energy Commission, Washington, D.C., 1971.
27. **Westman, W. E.**, How much are nature's services worth?, *Science*, 197(4307), 960, 1977.
28. **Abelson, P. H.**, Energy and climate, *Science*, 197(4307), 941, 1977.

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APPENDIX A

SOURCES OF INFORMATION

The radiation biologist is fortunate in that extensive sources of information are available. Such sources cater not only to the specialist, but also to the generalist, particularly teachers interested in introducing their students to the broad and complex subject of ionizing radiation. Numerous books concerning or related to ionizing radiation have been published; however, it is not within the scope of this book to list them unless they specifically involve radiation ecology. These should be readily available from any large library. Many publications are products of the U. S. Department of Energy (and its predecessors), particularly its Office of Technical Information, and the International Atomic Energy Agency. The Office of Technical Information is more than willing to assist persons searching for information. Periodically the International Atomic Energy Agency publishes a catalog of its publications.

The following selected list of bibliographies, proceedings and books concerning or related to radiation ecology was prepared to assist the reader in furthering his or her knowledge of radiation ecology. For those publications we consider rather difficult to locate, we have given the *Nuclear Science Abstracts* citation number when known. All titles are presented in English, even though the original title may have been in another language. If the publication is not available in English, the foreign language involved is indicated. As translations are continually appearing, it is possible that some of these may have been translated into English by the time this book appears in print.

Proceedings and Books

Åberg, B. and Hungate, F. P., Eds., *Radioecological Concentration Processes*, Pergamon Press, London, 1967.

Adams, J. A. S. and Lowder, W. M., Eds., *The Natural Radiation Environment*, Proc. Int. Symp. Natural Radiation Environment, University of Chicago Press, Ill., 1964.

Adams, J. A. S., Lowder, W. M., and Gesell, T. F., Eds., The Natural Radiation Environment II, Vols. 1 and 2, U.S. ERDA Reps. CONF-720805-P1 and CONF-720805-P2, Proc. 2nd Int. Symp. Natural Radiation Environment, U.S. Energy Research and Development Administration, Washington, D.C., no date.

Aleksahkin, R. M., *Radioactive Contamination of Soils and Plants*, Nauka, Moscow, 1963; (English transl., 1965; TT-66-51002; AEC-tr-6631, U.S. Atomic Energy Commission, Washington, D.C.); *Nucl. Sci. Abstr.*, 18(8), 12358.

Aleksakhin, R. M., Ed., *Radioecology of Animals* (in Russian), A. N. Severtsov Institute of Evolutional Morphology and Ecology of Animals, Nauka, Moscow, 1977.

Aleksakhin, R. M. and Naryshkin, M. A., *Migration of Radionuclides in Forest Biogeocoenoses* (in Russian), Nauka, Moscow, 1977.

Aleksakhin, R. M. and Karaban, R. T., Eds., Problems of Forest Radioecology (in Russian), Issue 38, Proc. Order of Labor of Red Banner Institute of Applied Geophysics, Moscow Division of Gidrometeroizdat, Russia, 1979.

Ancellin, J., Gueguéniat, P., and Germain, P., *Marine Radioecology. Study of Accumulation of Radionuclides Disposed into the Marine Environment and Application to Radiation Protection* (in French), Librairie de l'Enseignement Technique, Paris, 1979.

Andrushaitis, G. P., Ed., *Radioecology of Water Organisms* (in Russian), Vol. 1, Zinatne, Riga, 1972.

Andrushaitis, G. P., Ed., *Radioecology of Water Organisms* Vol. 2, Zinatne, Riga, 1973; AEC-tr-7606 (English transl.), U.S. Atomic Energy Commission, Washington, D.C., 1975; *Nucl. Sci. Abstr.*, 30(8), 21082; *Nucl. Sci. Abstr.*, 32(6), 14310.

Andrushaitis, G. P., Ed., *Radioecology of Water Organisms*, Vol. 3, Zinatne, Riga, 1973; AEC-tr-7529 (English transl.), U.S. Atomic Energy Commission, Washington, D.C., 1974; *Nucl. Sci. Abstr.*, 30(9), 24395; *Nucl. Sci. Abstr.*, 31(5), 11691.

Annekov, B. N., Dibobes, I. K., and Aleksakhin, R. M., *The Radiobiology and Radioecology of Farm Animals*, Atomizdat, Moscow, 1973; AEC-tr-7523 (English transl.), U.S. Atomic Energy Commission, Washington, D.C., *Nucl. Sci. Abstr.*, 28(5), 10882; *Nucl. Sci. Abstr.*, 29(12), 29863.

Anon., Proc. Int. Symp. Radioecology (in French and English), Vols 1 and 2, Commissariat a l'Energie Atomique, France, 1970; *Nucl. Sci. Abstr.*, 24(20), 41784.

Anon., Proc. Seminar on Marine Radioecology (in French), Organisation de Cooperation et de Developpement Economiques, Agence Europeenne pour l'Energie Nucleaire, Paris, no date; *Nucl. Sci. Abstr.*, 24(17), 34204.

Anon., *Int. Symp. Application of Neutron Activation Analysis in Oceanography*, Institut Royal des Sciences Naturelles de Belgique, Bruxelles, 1968; *Nucl. Sci. Abstr.*, 25(8), 15535.

Anon., *Proc. 1st Conf. State of Advancement of Radioecology in Italy* (in Italian), Centro Informazioni Studi Esperienze, Milan, 1970.

Anon., *Marine Radioecology, The Cycling of Artificial Radionuclides Through Marine Food Chains* (in English), Organisation de Cooperation et de Developpement Economiques, Paris, 1972; *Nucl. Sci. Abstr.*, 29(1), 405.

Anon., *Radioecological Conference: Theoretical and Practical Problems of the Contamination of the Environment with Radioactive Materials* (in Russian and Czech), Slovenska Vedeckotechnicka Spolocnost, Komisia pre Jadrovu Techniku, Kosice, Czechoslovakia, 1972; *Nucl. Sci. Abstr.*, 30(3), 6481.

Anon., *Proc. 2nd Conf. State of Advancement of Radioecology in Italy* (in Italian), Centro Informazioni Studi Experienze, Milan, 1973.

Anon., Proc. Seminar on Marine Radioecology (in French), Third NEA Seminar, Organisation de Cooperation et de Developpement Economiques, Agence Europeenne pour l'Energie, Paris, 1980.

Baranov, V. I. and Khitrov, L. M., Eds., *Radioactive Contamination of the Seas and Oceans* (in Russian), Nauka, Moscow, 1964 English transl., JPRS 26,002 (partial translation); AEC-tr-6641, U.S. Atomic Energy Commission, Washington, D.C., 1966; *Nucl. Sci. Abstr.*, 18(19), 33779; *Nucl. Sci. Abstr.*, 21(6), 8471.

Belousova, I. M. and Shtukkenberg, Yu. M., *Natural Radioactivity* (in Russian), Burnazyan, A. I., Ed.,

Bensen, D. W. and Sparrow, A. H., Eds., Survival of Food Crops and Livestock in the Event of Nuclear War, *(AEC Symp. Ser. 24)* U.S. AEC Rep. CONF-700909, U.S. Atomic Energy Commission, Washington, D.C., 1971.

Caldecott, R. S. and Snyder, L. A., Eds., *A Symposium on Radioisotopes in the Biosphere*, University of Minnesota Printing Department, Minneapolis, 1960.

Commission of the European Communities, *Proc. Int. Symp. Radioecology Applied to the Protection of Man and His Environment*, Vols. 1 and 2 (in various languages), Rep. EUR 48000 d-f-i-e, Commission of the European Communities, Luxembourg, 1971; *Nucl. Sci. Abstr.*, 27(3), 5273.

Committee on the Effects of Atomic Radiation on Oceanography and Fisheries, The Effects of Atomic Radiation on Oceanography and Fisheries, Publ. 551, National Academy of Sciences-National Research Council, Washington, D.C., 1957.

Committee to study the Long-Term Worldwide Effects of Multiple Nuclear-Weapons Detonation, *Long-Term Worldwide Effects of Multiple Nuclear—Weapons Detonations*, National Research Council, National Academy of Sciences, Washington, D.C., 1975.

Cullen, T. L. and Penna Franca, E., Eds., *Int. Symp. Areas of High Natural Radioactivity*, Academia Brazileira de Ciencias, Rio de Janeiro, Brazil, 1977; U.S. ERDA No. CONF-750671, U.S. Energy Research and Development Administration, Washington, D.C., 1977; *ERDA Energy Res. Abstr.*, 2(16), 40196.

Cushing, C. E., Jr. et al., Eds., *Radioecology and Energy Resources*, Dowden, Hutchinson & Ross, Stroudsburg, Pa., 1976.

Dunaway, P. B. and White, M. G., Eds., The Dynamics of Plutonium in Desert Environments, U.S. AEC Rep. NVO-142, Nevada Applied Ecology Group Prog. Rep. January 1974, Nevada Operations Office, Las Vegas, 1974.

Egami, N., Ed., *Radioactivity and Fishes (Contamination, Injury and Utilization)* (in Japanese), Koseisha-koseikaku, Tokyo, 1973; *Nucl. Sci. Abstr.*, 29(6), 13023 to 13025, 13027, 16004, 16005.

Eisenbud, M., *Environmental Radioactivity*, 2nd ed., Academic Press, New York, 1973.

Ferronskiy, V. I., *Natural Isotopes of the Hydrosphere* (in Russian), Nedra, Moscow, 1975; *Nucl. Sci. Abstr.*, 33(8), 17175.

Fontaine, Y., Radioactive Contamination of Aquatic Media and Organisms, (in French), Rep. CEA-1588, Commissariat a l'Energie Atomique, Centre d'Etudes Nucleaires, Saclay, France, 1960; AEC-tr-5358 (English transl.), U.S. Atomic Energy Commission, Washington, D.C., 1962; *Nucl. Sci. Abstr.*, 15(15), 19131.

Fowler, E. B., Ed., *Radioactive Fallout, Soils, Plants, Foods, Man*, American Elsevier, New York, 1965.

Gesell, T. F. and Lowder, W. M., Eds., *Natural Radiation Environment III*, Vols. 1 and 2, U. S. DOE Rep. CONF-780422, U. S. Department of Energy, Washington, D. C., 1980.

Gromov, V. V. and Spitsyn, V. I., *Artificial Radionuclides in the Marine Environment* (in Russian), Atomizdat, Moscow, 1975; *Nucl. Sci. Abstr.*, 33(11), 26325.

Hanson, W. C., Ed., Transuranic Elements in the Environment, U.S. DOE Rep. DOE/TIC-22800, U.S. Department of Energy, Washington, D.C., 1980.

Hines, N. O., *Proving Ground: An Account of the Radiobiological Studies in the Pacific, 1946—1961*, University of Washington Press, Seattle, 1962.

Hungate, F. P., Ed., Radiation and terrestrial ecosystems, *Health Phys.*, 11(12), 1965.

IAEA, Disposal of Radioactive Wastes, Vols. 1 and 2, Publ. STI/PUB/18, International Atomic Energy Agency, Vienna, 1960.

IAEA, Environmental Contamination by Radioactive Materials, Publ. STI/PUB/226, International Atomic Energy Agency, Vienna, 1969.

IAEA, Disposal of Radioactive Wastes into Seas, Oceans and Surface Waters, Publ. STI/PUB/126, International Atomic Energy Agency, Vienna, 1969.

IAEA, Reference Methods for Marine Radioactivity Studies, Tech. Rep. Ser. No. 118 (Publ. STI/DOC/10/118), International Atomic Energy Agency, Vienna, 1970.

IAEA, Environmental Aspects of Nuclear Power Stations, Publ. STI/PUB/261, International Atomic Energy Agency, Vienna, 1971.

IAEA, Nuclear Techniques in Environmental Pollution, Publ. STI/PUB/268, International Atomic Energy Agency, Vienna, 1971.

IAEA, Environmental Behaviour of Radionuclides Released in the Nuclear Industry, Publ. STI/PUB/345, International Atomic Energy Agency, Vienna, 1973.

IAEA, Radioactive Contamination of the Marine Environment, Publ. STI/PUB/313, International Atomic Energy Agency, Vienna, 1973.

IAEA, Combined Effects of Radioactive, Chemical, and Thermal Releases to the Environment, Publ. STI/PUB/404, International Atomic Energy Agency, Vienna, 1975.

IAEA, Design of Radiotracer Experiments in Marine Biological Systems, Tech. Rep. Ser. No. 167 (Publ. STI/DOC/10/167), International Atomic Energy Agency, Vienna, 1975.

IAEA, Impacts of Nuclear Releases into the Aquatic Environment, Publ. STI/PUB/406, International Atomic Energy Agency, Vienna, 1975.

IAEA, Isotope Ratios as Pollutant Source and Behaviour Indicators, Publ. STI/PUB/382, International Atomic Energy Agency, Vienna, 1975.

IAEA, Reference Methods for Marine Radioactivity Studies II, Tech. Rep. Ser. No. 169 (Publ. STI/DOC/10/169), International Atomic Energy Agency, Vienna, 1975.

IAEA, Effects of Ionizing Radiation on Aquatic Organisms and Ecosystems, Tech. Rep. Ser. No. 172 (Publ. STI/DOC/10/172), International Atomic Energy Agency, Vienna, 1976.

IAEA, Transuranium Nuclides in the Environment, Publ. STI/PUB/410, International Atomic Energy Agency, Vienna, 1976.

IAEA, Methodology for Assessing Impacts of Radioactivity on Aquatic Ecosystems, Tech. Rep. Ser. No. 190 (Publ. STI/DOC/10/190), International Atomic Energy Agency, Vienna, 1979.

Japan Society for the Promotion of Science, *Research in the Effects and Influences of the Nuclear Bomb Test Explosions*, Vols. 1 and 2, Ueno, Tokyo, Japan, 1956, (in English and Japanese editions.)

Kalmykov, P. G., *Effects of Ionizing Radiations on Insects* (in Russian), Atomizdat, Moscow, 1970; *Nucl. Sci. Abstr.*, 25(11), 24316.

Klechkovskiy, V. M., Polikarpov, G. G., and Aleksakhin, R. M., Eds., *Radioecology, Contemporary Problems of Radiobiology*, Vol. 2, Atomizdat, Moscow, 1971; *Radioecology* (English transl.), Greenberg, D., Ed., John Wiley & Sons, New York, 1973; *Nucl. Sci. Abstr.*, 29(6), 12716.

Kornegay, B. H., Vaughan, W. A., Jamison, D. K. and Morgan, J. M., Jr., Eds., Transport of Radionuclides in Fresh Water Systems, U.S. AEC Rep. TID-7664, U.S. Atomic Energy Commission, Washington, D.C., 1963.

Kulikov, N. V. and Molchanova, I. V., *Continental Radioecology (Soil and Freshwater Ecosystems)* (in Russian), Nauka, Moscow, 1975.

Kulikov, N. V. and Chebotina, M. Ya., Eds., *Problems of Radioecology of Water Cooling Bodies of Atomic Power Plants* (in Russian), Proc. Institute of Plant and Animal Ecology, Urals Scientific Centre of USSR Academy of Sciences, Sverdlovsk, 1978, Issue 110.

Kuzin, A. M., Maslova, K. I., Ovchenkov, V. Ya., and Borodkin, P. A., Eds., *Problems of Radioecology and Biological Effects of Low Doses of Ionizing Radiation* (in Russian), Academy of Sciences of USSR, Syktyvkar, 1976.

Lebedinskiy, A. V. and Moskalev, Yu. I., Eds., *Distribution, Biological Effects, and Migration of Radioactive Isotopes*, Medgiz, Moscow, 1961; AEC-tr-7612 (English transl.), U.S. Atomic Energy Commission, Washington, D.C., no date; *Nucl. Sci. Abstr.*, 18(9), 13396; *Nucl. Sci. Abstr.*, 30(3), 7147.

Markham, O. D., Ed., Summaries of the Idaho National Engineering Laboratory Site Ecological Studies Information Meeting July 10 to 11, 1975 at the Idaho National Engineering Laboratory Site, U.S. ERDA Rep. IDO-12079, Idaho Operations Office, Idaho Falls, 1976.

Markham, O. D. and Arthur, W. J., Eds., Proc. Symp. Idaho National Engineering Laboratory Ecology Programs, U.S. DOE Rep. IDO-12088, Idaho Operations Office, Idaho Falls, 1979.

Merritt, M. L. and Fuller, R. G., Eds., The Environment of Amchitka Island, Alaska, U.S. ERDA Rep. TID-26712, U.S. Energy Research and Development Administration, Washington, D.C., 1977.

Miller, M. W. and Stannard, J. N., Eds., *Environmental Toxicity of Aquatic Radionuclides: Models and Mechanisms*, Ann Arbor Science Publishers, Mich., 1976.

Moiseyev, A. A. and Ramzaev, P. B., *Cesium-137 in the Biosphere* (in Russian), Atomizdat, Moscow, 1975; *Nucl. Sci. Abstr.*, 33(11), 25998.

Molchanova, I. V. and Kulikov, N. V., *Radioactive Isotopes in Soil-Plant Systems* (in Russian), Atomizdat, Moscow, 1972; *Nucl. Sci. Abstr.*, 33(5), 9282.

Nelson, D. J., Ed., *Radionuclides in Ecosystems*, Vols. 1 and 2, Proc. 3rd Natl. Symp. Radioecology, U.S. AEC Rep. CONF-710501-P1 and CONF-710501-P2, U.S. Atomic Energy Commission, Washington, D.C., 1973.

Nelson, D. J. and Evans, F. C., Eds., Symposium on Radioecology, U.S. AEC Rep. CONF-670503, U.S. Atomic Energy Commission, Washington, D.C., 1969.

Odum, H. T. and Pigeon, R. F., Eds., A Tropical Rain Forest: A Study of Irradiation and Ecology at El Verde, Puerto Rico, U.S. AEC Rep. TID-24270 (PRNC-138), U.S. Atomic Energy Commission, Washington, D.C., 1970.

Ostroumov, E. A., Ed., *Chemical Analysis of Marine Sediments* (in Russian), Nauka, Moscow, 1975; *Nucl. Sci. Abstr.*, 33(5), 8847.

Panel on Radioactivity in the Environment, *Radioactivity in the Marine Environment*, National Academy of Sciences, Washington, D.C., 1971.

Parchevskaya, D. S., *Statistics for Radioecologists (Practical Guide on Statistics and Planning of Experiments in Radioecology)* (in Russian), Naukova Dumka, Kiev, 1969.

Pavlotskaya, F. I., *Migration of Radioactive Fallout Products in Soils* (in Russian), Atomizdat, Moscow, 1974; *Nucl. Sci. Abstr.*, 31(1), 536.

Pertsov, L. A., *The Natural Radioactivity of the Biosphere*, Atomizdat, Moscow, 1964; AEC-tr-6714 (English transl.), U.S. Atomic Energy Commission, Washington, D.C., 1967; *Nucl. Sci. Abstr.*, 19(1), 24.

Pertsov, L. A., Ed., *Marine Radioecology* (in Russian), Atlanticheskiy Nauchno-Issledovatel'skiy Institut Rybnogo Khozyaistva i Okeanografiy, Kaliningrad, U.S.S.R., 1971, Issue 44; *Nucl. Sci. Abstr.*, 30(1), 311.

Pertsov, L. A., Ed., *Marine Radioecology* (in Russian), Atlanticheskiy Nauchno-Issledovatel'skiy Institut Rybnogo Khozyaistva i Okeanografiy, Kaliningrad, U.S.S.R., 1971, Issue 45; *Nucl. Sci. Abstr.*, 30(1), 312.

Pertsov, L. A., *Ionizing Radiation in the Biosphere* (in Russian), Atomizdat, Moscow, 1973; *Nucl. Sci. Abstr.*, 29(2), 2637.

Pertsov, L. A., *Biological Aspects of Radioactive Contamination of the Sea* (in Russian), Atomizdat, Moscow, 1978.

Petri, V. N., Ed., *Effects of Ionizing Radiation on Hydrobionts and Land Plants* (in Russian), Trudy Instituta Ekologii Rastenii Zhivotnykh, U.S.S.R., 1970, 74; *Nucl. Sci. Abstr.*, 25(11), 24462.

Polikarpov, G. G., *Radioecology of Aquatic Organisms* (English transl. and revised edition), Schultz, V. and Klement, A. W., Jr., Eds., North-Holland, Amsterdam, 1966; *Radioecology of Marine Organisms* (original), Atomizdat, Moscow, 1964; *Nucl. Sci. Abstr.*, 18(19), 33230; *Nucl. Sci. Abstr.*, 21(12), 20115.

Polikarpov, G. G., Ed., *Marine Radioecology*, Naukova Dumka, Kiev, 1970; AEC-tr-7299 (English transl.), U.S. Atomic Energy Commission, Washington, D.C., 1972; *Nucl. Sci. Abstr.*, 25(15), 35117; *Nucl. Sci. Abstr.*, 26(10), 23186.

Polikarpov, G. G., Ed., *Radiochemo-Ecological Investigations in the Mediterranean Sea* (in Russian with English summaries), Naukova Dumka, Kiev, 1975.

Polikarpov, G. G., Ed., *Chemoradioecology of the Pelagic and the Benthic Zones. (Metals and Radionuclides in Aquatic Organisms and Environment)* (in Russian), Naukova Dumka, Kiev, 1974; *Nucl. Sci. Abstr.*, 30(11), 29422.

Polikarpov, G. G., Ed., *Radiochemo-Ecologieal Investigations in the Mediterranean Sea* (in Russian), Naukova Dumka, Kiev, 1975.

Polikarpov, G. G. and Parchevsky, V. P., Eds., *Methods of Determination of Radioactivity* (in Russian), Naukova Dumka, Kiev, 1972; *Nucl. Sci. Abstr.*, 29(2), 2461.

Polikarpov, G. G. and Risik, N. S., Eds., *Radiochemo-Ecology of the Black Sea* (in Russian), Naukova Dumka, Kiev, 1977.

Polikarpov, G. G., Zaitsev, Yu. P., Kulebakina, L. G., Timoshchuk, V. I., Tsytsugina, V. G., Rozhanskaya, L. I., Risik, N. S., Strogonov, A. A., and Zesenko, A. Ya., *Radioecological Investigations of the Mediterranean Sea* (in Russian), Naukova Dumka, Kiev, 1970; *Nucl. Sci. Abstr.*, 25(5), 8630.

Popov, N. I., Ed., *Forms of Elements and Radionuclides in Sea Water* (in Russian), Nauka, Moscow, 1974.

Pruter, A. T. and Alverson, D. L., Eds., *The Columbia River Estuary and Adjacent Ocean Waters: Bioenvironmental Studies*, University of Washington Press, Seattle, 1972.

Schultz, V. and Klement, A. W., Jr., Eds., *Radioecology*, Proc. 1st Natl. Symp. Radioecology, Colorado State University, Ft. Collins, 1961, Reinhold, New York, 1963.

Schultz, V. and Whicker, F. W., Ecological Consequences of the Nuclear Age: Selected Readings in Radiation Ecology, U.S. AEC Rep. TID-25978, U.S. Atomic Energy Commission, Washington, D.C., 1972.

BEST AVAILABLE COPY

Schultz, V. and Whicker, F. W., *Radioecological Techniques,* Plenum Press, New York, 1982.
Shvarts, S. S., Ed., *Problems of the Radioecology of Aqueous Organisms* (in Russian), Trudy Instituta Ekologii Rastenii Zhivotnykh, 1971, 78; *Nucl. Sci. Abstr.*, 26(12), 28093.
Shvedov, V. P. and Patin, S. A., *Radioactivity in the Oceans and Seas* (in Russian), Atomizdat, Moscow, 1968; *Nucl. Sci. Abstr.*, 22(24), 51122.
Small, S. H., Ed., Nuclear Detonations and Marine Radioactivity, Rep. Symp., Norwegian Defense Research Establishment, 16 to 20 September 1963, Norwegian Defense Research Establishment, Kjeller, Norway, 1963; *Nucl. Sci. Abstr.*, 19(13), 24714.
Sokolova, I. A., *Calcium, Strontium-90, and Strontium in Marine Organisms* (in Russian), Naukova Dumka, Kiev, 1971; *Nucl. Sci. Abstr.*, 26(18), 43396.
Sorokin, B. P., Ed., *Effect of Ionizing Radiation on the Organism. The Problem of the Effect of Radioactive Water Pollution on the Reproduction of Commercial Fishes,* Trudy Polyarnye Nauchno-Issledovatel'shiy Institut Rybnogo Khozyaistva i Okeanografiy, 1971, 29; AEC-tr-7418 (English transl.), U.S. Atomic Energy Commission, Washington, D.C., 1973; *Nucl. Sci. Abstr.*, 27(12), 27944.
Tikhomirov, F. A., *Effect of Ionizing Radiation on Ecological Systems* (in Russian), Atomizdat, Moscow, 1972; *Nucl. Sci. Abstr.*, 33(4), 7288.
Tsytsugina, V. G., Risik, N. S., and Lazorenko, G. E., *Artificial and Natural Radionuclides in Marine Life,* Naukova Dumka, Kiev, 1973; TT 75-50010 (English transl.), 1975; *Nucl. Sci. Abstr.*, 28(7), 15818; *Nucl. Sci. Abstr.*, 29(9), 21246; *Nucl. Sci. Abstr.*, 33(8), 17173.
Verkhovskaya, I. N., Ed., *Methods of Radioecological Investigations* (in Russian) Atomizdat, Moscow, 1971; *Nucl. Sci. Abstr.*, 26(6), 12255.
Verkhovskaya, I. N., Ed., *Radioecological Investigations in Natural Biogeocenoses* (in Russian), Nauka, Moscow, 1972; *Nucl. Sci. Abstr.*, 26(23), 56134.
Wallace, A. and Romney, E. M., Radioecology and Ecophysiology of Desert Plants at the Nevada Test Site, U.S. AEC Rep. TID-25954, U.S. Atomic Energy Commission, Washington, D.C., 1972.
White, M. G. and Dunaway, P. B., Eds., Transuranics in Natural Environments, U.S. ERDA Rep. NVO-178, Nevada Operations Office, Las Vegas, 1977.
Wilimovsky, N. J. and Wolfe, J. N., Eds., Environment of the Cape Thompson Region, Alaska, U.S. AEC Rep. PNE-481, U.S. Atomic Energy Commission, Washington, D.C., 1966.
Woodwell, G. M., Ed., Ecological Effects of Nuclear War, U.S. AEC Rep. BNL-917(C-43), Brookhaven National Laboratory, Upton, Long Island, N.Y., 1965.
Zavitkovski, J., Ed., The Enterprise, Wisconsin, Radiation Forest. Radioecological Studies, U.S. ERDA Rep. TID-26113-P2, U.S. Energy Research and Development Administration, Washington, D.C., 1977.
Zoological Station of Naples, Italy, Marine biological applications of radio-isotope research techniques, *Pubbl. Stn. Zool. Napoli,* 31(suppl.), 1959.

Bibliographies

Amiard, J.- C., Etude bibliographique de l'influence de la temperature sur la radiocontamination des organismes aquatiques, in Influence de L'elevation de la Temperature de l'eau sur la Radiocontamination des Organismes Aquatiques, Rep. E31/78/No. 25, ARD E3DO4, Electricite de France, Paris, 1978, A1.
Anon., Environmental Studies at the Savannah River Plant and Immediate Environs. A Bibliography. U.S. ERDA Rep. TID-3353, U.S. Energy Research and Development Administration, Washington, D.C., 1975.
Anon., Liste des Publications (in French), Section de Radioecologie, Commissariat a l'Energie Atomique, Centre d'Etudes Nucleaires de Cadarache, Saint-Paul-Lez-Durance, France, 1976.
Anon., Liste des Publications (in French), Section de Radioecologie, Department de Protection, Institut de Protection et de Surete Nucleaire, Commissariat a l'Energie Atomique, Centre d'Etudes Nucleaires de Cadarache, Cadarache, France, 1978.
Becker, C. D., Aquatic Bioenvironmental Studies in the Columbia River at Hanford 1945-1971. A Bibliography with Abstracts, U.S. AEC Rep. BNWL-1734, Battelle Northwest Laboratory, Richland, Wash., 1973.
Binggeli, M., Radioisotopes and Ionizing Radiation in Entomology, Bibl. Ser. No. 9,; No. 15,; No. 24,; and No. 36,; (STI/PUB/21/9), (STI/PUB/21/15), (STI/PUB/21/24), (STI/PUB/21/36), respectively, International Atomic Energy Commission, Vienna, 1963; 1965; 1967; 1969; respectively.
Deutsches Hydrographisches Institut, Bibliographies in Nuclear Science and Technology, Section 25, Maritime Radioecology (Various languages), Rep. AED-C-25-01, 1967; AED-C-02, 1968; AED-C-25-03, 1973; AED-C-25-04, 1973, Zentralstelle fur Atomkernenergi-Dokumentation, Frankfurt/Main, Germany; *Nucl. Sci. Abstr.*, 22(2), 2254; *Nucl. Sci. Abstr.*, 29(8), 18354 and 18355.
Disdier, R. and Michon, G., Radioactivity and Ecology (in French), Rep. CEA-Bib-22, Commissariat a l'Energie Atomique, Centre d'Etudes Nucleaires, Saclay, France, 1962.
Ecological Sciences Information Center, Environmental Sciences Division Publ. 1-500, An Abstracted, Indexed Bibliography, U.S. AEC Rep. ORNL-TM-4545, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1974; *Nucl. Sci. Abstr.*, 30(7), 18590.

Edmundson, E., Jr., Schultz, V., and Klement, A. W., Jr., Marine Radioecology: A Selected Bibliography of NonRussian Literature, U.S. AEC Rep. TID-3917, 1969; TID-3917 (Suppl. 1), 1972; TID-3917 (Suppl. 2), 1974, U.S. Atomic Energy Commission, Washington, D.C.

Engstrom, J. L., Ed., A Bibliography of Environmental Research: Ecosystems Department 1952-1973, U.S. AEC Rep. BNWL-SA-4655, Battelle Northwest, Richland, Wash., 1973.

Klement, A. W., Jr., Natural Environmental Radioactivity: An Annotated Bibliography, U.S. AEC Rep. WASH-1061, 1965; WASH-1061 (Suppl.), 1970, U.S. Atomic Energy Commission, Washington, D.C.

Klement, A. W., Jr. and Schultz, V., Terrestrial and Freshwater Radioecology: A Selected Bibliography, U.S. AEC Rep. TID-3910, 1962; TID-3910 (Suppl. 1), 1963; TID-3910 (Suppl. 2), 1964; TID-3910 (Suppl. 3), 1965; TID-3910 (Suppl. 4), 1966; TID-3910 (Suppl. 5), 1968; TID-3910 (Suppl. 6), 1970; TID-3910 (Suppl. 7), 1971; TID-3910 (Suppl. 8), 1972; TID-3910 (Suppl. 9), 1974; TID-3910-S10, 1975; U.S. Atomic Energy Commission, Washington, D.C.; U.S. ERDA Rep., TID-3910-S11, U.S. Energy Research and Development Administration, Washington, D.C., 1975; U.S. DOE Rep. TID-3910-S12, U.S. Department of Energy, Washington, D.C., 1978.

Klement, A. W., Jr. and Schultz, V., Russian Radioecology: A Bibliography of Soviet Publications with Citations of English Translations and Abstracts, U.S. AEC Rep. TID-3915 (Suppl. 1), U.S. Atomic Energy Commission, Washington, D.C., 1972.

Klement, A. W., Jr. and Wallen, I. E., A selected list of references on marine and aquatic radiobiology, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 729; U.S. AEC Rep. TID-3903, U.S. Atomic Energy Commission, Washington, D.C., 1960.

Klement, A. W., Jr., Lytle, C. F., and Schultz, V., Russian Radioecology: A Bibliography of Soviet Publications with Citations of English Translations and Abstracts, U.S. AEC Rep. TID-3915, U.S. Atomic Energy Commission, Washington, D.C., 1968.

Lattimer, J. M., Estuarine Radioecology: A Bibliography of Report Literature, Bibl. Ser. No. 16, Office of Library Services, U.S. Department of Interior, Washington, D.C., 1970.

Markham, O. D., National Reactor Testing Station Environmentally Related Publications, U.S. AEC Rep. IDO-12078, Idaho Operations Office, Idaho Falls, 1973.

Oen, C., A Bibliography on Radioecology, U.S. AEC Rep. ORNL-EIS-71-10, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1972.

O'Farrell, T. P. and Christensen, V. K., A Bibliography of Environmental Research: Ecosystems Department 1952-1970, U.S. AEC Rep. BNWL-1549, Battelle Northwest, Richland, Wash., 1971.

O'Farrell, T. P. and Emery, L. A., Ecology of the Nevada Test Site: A Narrative Summary and Annotated Bibliography, U.S. ERDA Rep. NVO-167, Nevada Operations Office, Las Vegas, 1976.

O'Leary, J. M. and Roberts, I. C., Disposal of Radioactive Wastes into Marine and Fresh Waters, Bibl. Ser. No. 5 (STI/PUB/21/5), International Atomic Energy Agency, Vienna, 1962.

Polikarpov, G. G., Ed.; Exuz'yan, Z. M., Yegorov, V. N., and Kurilova, N. V., Compls., *Bibliographical Index of Publications of Institute of Biology of South Seas AS Ukr. SSR on the Problem of "Radiation and Chemical Ecology" (1957-1972)* (in Russian), Naukova Dumka, Kiev, 1974, Nucl. Sci. Abstr., 30(9), 24150.

Reichle, D. E., Nelson, D. J., and Dunaway, P. B., Biological Concentration and Turnover of Radionuclides in Food Chains: A Bibliography, U.S. AEC Rep. ORNL-NSIC-89 (ORNL-TM-2492), Oak Ridge National Laboratory, Oak Ridge, Tenn., 1971.

Schultz, V., Radionuclides and Ionizing Radiation in Ornithology: A Selected Bibliography on Wild and Domestic Birds, U.S. AEC Rep. TID-17762, U.S. Atomic Energy Commission, Washington, D.C., 1963.

Schultz, V., Ecological Techniques Utilizing Radionuclides and Ionizing Radiation: A Selected Bibliography, U.S. AEC Rep. RLO-2213-1, 1969; RLO-2213-1 (Suppl. 1), 1972, U.S. Atomic Energy Commission, Washington, D.C., U.S. ERDA Rep. RLO-2213 (Suppl. 2), U.S. Energy Research and Development Administration, Washington, D.C., 1975.

Schultz, V., Ionizing Radiation and Wild Birds: A Selected Bibliography, U.S. ERDA Rep. TID-3919, U.S. Energy Research and Development Administration, Washington, D.C., 1975.

Schultz, V., Russian Radioecology: A Bibliography of Soviet Publications with Citations of English Translations and Abstracts, U.S. ERDA Rep. TID-3915 (Suppl. 2), U.S. Energy Research and Development Administration, Washington, D.C., 1976.

Schultz, V., A Bibliography of Marine Radiation Ecology Prepared for the Seabed Program, Rep. SAND 79-7102, Sandia Laboratories, Albuquerque, N.M., 1980.

Schultz, V., Uptake and Retention of Radionuclides by Marine Organisms: A Bibliography Prepared for the Seabed Program, Rep. SAND 80-7133, Sandia Laboratories, Albuquerque, N.M., 1980.

Schultz, V. and Whicker, F. W., A Selected Bibliography of Terrestrial, Freshwater and Marine Radiation Ecology, U.S. AEC Rep. TID-25650, U.S. Atomic Energy Commission, Washington, D.C., 1971; U.S. ERDA Rep. TID-25650-S1, U.S. Energy Research and Development Administration, Washington, D.C., 1975.

Sparrow, A. H., Binnington, J. B., and Pond, V., Bibliography on the Effects of Ionizing Radiations on Plants, 1896-1955, U.S. AEC Rep. BNL-504(L-103), Brookhaven National Laboratory, Richland, Wash., 1958.

Triulzi, C., Scientific activities of the members of the Marine Radioactivity Committee and related bibliography (1973-1976), *Rapp. Comm. Int. Mer. Medit.*, 24(3), 107, 1977.

Ulrikson, G. U., Bopp, C. D., and Carroll, R. M., Indexed Bibliography on Effects of Radionuclides and Ionizing Radiation on Ecological Systems, U.S. AEC Rep. ORNL-NSIC-95, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1971.

Various authors, Radioactivity in the sea, in *Geochemical Study of the Ocean and the Atmosphere, Yasuo Mikake Seventieth Anniversary, Collected papers (1939-1977)*, Geochemical Laboratory, Meterological Research Institute, Tokyo, Japan, 1978, 247.

Vaughan, B. E. and Helbling, J. L., A Bibliography of Environmental Research: Ecosystems Department 1952-1978, Rep. PNL-SA-4655 (Rev. 4), Battelle Pacific Northwest Laboratories, Richland, Wash., 1978.

White, M. G. and Pfuderer, H. A., Nevada Applied Ecology Group Publications, U.S. DOE Rep. ORNL/EIS-127, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1978.

APPENDIX B

LITERATURE REVIEWS OF SPECIFIC RADIONUCLIDES IN THE ENVIRONMENT

Auerbach, S. I. and Olson, J. S., Biological and environmental behavior of ruthenium and rhodium, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 509.

Bittel, R., Bibliographic Discussion of the Physico-Chemical Behavior and the Radioecology of Ruthenium in Hydrobiological Systems (in French), Rep. CEA-Bib-123, Commissariat a l'Energie Atomique, Centre d'Etudes Nucleaires, Fontenay-Aux-Roses, France, 1968; *Nucl Sci. Abstr.*, 22(24), 51486.

Bittel, R., Bibliographic Discussion of the Physico-Chemical Behavior and the Radioecology in Hydrobiological Systems of Cerium and Other Lanthanides (in French), Rep. CEA-Bib-138, Commissariat a l'Energie Atomique, Centre d'Etudes Nucleaires, Fontenay-aux-Roses, France, 1969; *Nucl. Sci. Abstr.*, 23(21), 43715.

Clajus, P., Ecology of Radium. A Literature Survey (in German), Rep. SAAS-183, Staatliches Amt fuer Atomsicherheit und Strahlenschutz, Berlin, German Democratic Republic, 1975; *Nucl. Sci. Abstr.*, 33(6), 12009.

Crowson, D. L., Man-made tritium, in *Tritium*, Moghissi, A. A. and Carter, M. W., Eds., Messenger Graphics, Phoenix, Ariz., 1973, 23; *Nucl. Sci. Abstr.*, 28(11), 27223.

Davis, J. J., Cesium and its relationships to potassium in ecology, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 539.

Elwood, J. W., Ecological aspects of tritium behavior in the environment, *Nucl. Saf.*, 12(4), 326, 1971.

Foster, R. F., Environmental behavior of chromium and neptunium, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 569.

Francis, C. W., Plutonium mobility in soil and uptake in plants: a review, *J. Environ. Qual.*, 2(1), 67, 1973.

Francis, C. W., Radiostrontium Movement in Solids and Uptake in Plants, U.S. DOE Rep. TID-27564 (DOE Critical Review Series), U.S. Department of Energy, Washington, D.C., 1978.

French, N. R., Review and discussion of barium, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 557.

Hakonson, T. E., Environmental pathways of plutonium into terrestrial plants and animals, *Health Phys.*, 29(4), 583, 1975.

Hanson, W. C., Iodine in the environment, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 581.

Hanson, W. C., Ecological considerations of the behavior of plutonium in the environment, *Health Phys.*, 28(5), 529, 1975.

Hanson, W. C., Ecological considerations of natural and depleted uranium, in The Natural Radiation Environment III, Vol. 2, Gesell, T. F. and Lowder, W. M., Eds., U.S. DOE Rep. CONF-780422, U.S. Department of Energy, Washington, D.C., 1980.

Held, E. E., Some aspects of the biology of zirconium-95, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 577.

Hsiao, S. C., The radioecology of calcium, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 525.

IAEA, Tritium and Other Environmental Isotopes in the Hydrological Cycle, Tech. Rep. Ser. No. 73 (Publ. STI/DOC/10/73), International Atomic Energy Agency, Vienna, 1967.

Jacobs, D. G., Sources of Tritium and its Behavior Upon Release to the Environment, U.S. AEC Rep. TID-24635, U.S. Atomic Energy Commission, Washington, D.C., 1968.

Junkins, R. L., Arsenic and its radioisotopes in the environs, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 615.

Kirk, W. P., ^{85}Kr: A Review of the Literature and an Analysis of Radiation Hazards, U.S. EPA Rep. NP-19251, Eastern Environmental Radiation Laboratory, 1972.

Koczy, F. F., The natural radioactive series in organic material, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 611.

Lowman, F. G., Iron and cobalt in ecology, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 561.

Moiseyev, A. A. and Ramzaev, P. B., *Cesium-137 in the Biosphere* (in Russian), Atomizdat, Moscow, 1975; *Nucl. Sci. Abstr.*, 33(11), 25998.

Nishita, H., A Review of Behavior of Plutonium in Soils and Other Geologic Materials, U.S. NRC Rep. NUREG/CR-1056, U.S. Nuclear Regulatory Commission, Washington, D.C., 1979.

Noshkin, V. E., Ecological aspects of plutonium dissemination in aquatic environments, *Health Phys.*, 22(6), 537, 1972.

Olafson, J. H. and Larson, K. H., Plutonium, its biology and environmental persistance, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York 1963, 633.

BEST AVAILABLE COPY

Palumbo, R. F., Factors controlling the distribution of the rare earths in the environment and in living organisms, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 533.
Parfenov, Yu. D., Polonium-210 in the environment and in the human organism, *At. Energy Rev.*, 12(1), 75, 1974.
Price, K. R., A review of transuranic elements in soils, plants, and animals, *J. Environ. Qual.*, 2(1), 62, 1973.
Rice, T. R., Review of zinc in ecology, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 619.
Romney, E. M. and Childress, J. D., Reactions of tungsten in soils and its uptake by plants, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 521.
Romney, E. M. and Davis, J. J., Ecological aspects of plutonium dissemination in terrestrial environments, *Health Phys.*, 22(6), 551, 1972.
Schell, W. R. and Watters, R. L., Plutonium in aqueous systems, *Health Phys.*, 29(4), 589, 1975.
Skauen, D. M., Tritium in ecology — a review, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 603.
Templeton, W. L., Dosimetry and ecological effects of transuranics in the marine environment, in Transuranic Elements in the Environment, U.S. DOE report DOE/TIC-22800, Hanson, W. C., Ed., U.S. Department of Energy, Washington, D.C., 1980, 714.
Volchok, H., Bowen, V., Dyer, R., Forster, W., Herring, J., Perkowski, J., Rice, T., and Stannard, J., Transuranic elements, in *Assessing Potential Ocean Pollutants*, National Academy of Sciences, Washington, D.C., 1975, 27.
Wangersky, P. J., Manganese in ecology, in *Radioecology*, Schultz, V. and Klement, A. W., Jr., Eds., Reinhold, New York, 1963, 499.
Whicker, F. W., Ecological effects of transuranics in the terrestrial environment, in Transuranic Elements in the Environment, U.S. DOE Rep. DOE/TIC-22800, Hanson, W. C., Ed., U.S. Department of Energy, Washington, D.C., 1980, 701.

APPENDIX C

TABLE OF RADIONUCLIDES: PHYSICAL HALF-LIFES AND MAJOR RADIATIONS

A list of radionuclides with their physical half-lives and major radiations has been compiled for the interested reader in Table 1. Table 1 includes those radionuclides for which a maximum permissible concentration for man (MPC) has been listed.[1,2] Selected radionuclides not listed in these publications are also included. The primary source of physical half-life data was Heath[3] with supplementary information from Lederer et al.[4] The latter publication was the source of the tabulated "major radiations".

Preceding Table 1 is a bibliography of other major publications on these and other characteristics of radionuclides. Revised editions of some of the listed material may be available.

REFERENCES

1. **Altman, P. L. and Dittmer, D. S., Comp.; Ed.,** Maximum permissible occupational exposure to ionizing radiation: man, in *Environmental Biology*, Federation of American Societies for Experimental Biology, Bethesda, Md., 1966, 165.
2. **National Committee on Radiation Protection,** Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure, Handbook 69, National Bureau of Standards, U.S. Department of Commerce, Washington, D.C., 1959.
3. **Heath, R. L.,** Table of the isotopes, in *Handbook of Chemistry and Physics*, 52nd ed., Weast, R. C., Ed., Chemical Rubber Co., Boca Raton, Fla., 1971, B245.
4. **Lederer, C. M., Hollander, J. M., and Perlman, I.,** *Table of Isotopes*, 6th ed., John Wiley & Sons, New York, 1967.

OTHER SOURCES OF INFORMATION ON CHARACTERISTICS OF RADIONUCLIDES

Division of Radiological Health, Radiological Health Handbook, rev. ed., Rep. PB 121784R, U.S. Public Health Service, Washington, D.C., 1970.

Goldman, D. T. and Roesser, J. R., *Chart of the Nuclides*, 9th ed., General Electric Co., Schenectady, N.Y., 1966.

Hogerton, J. F., Ed., *Atomic Energy Deskbook*, Reinhold, New York, 1963.

International Commission on Radiological Protection, Report of Committee II on permissible dose for internal radiation (1959), *Health Phys.*, 3, 1, 1960.

Lauriston, S. T., *Radiation Protection Standards*, Chemical Rubber Co., Boca Raton, Fla., 1971.

Schilling, C. W. and Shilling, M. T., *Atomic Energy Encyclopedia in the Life Sciences*, W. B. Saunders, Philadelphia, 1964.

Slack, L. and Way, K., Radiations from Radioactive Atoms in Frequent Use, U.S. Atomic Energy Commission, Washington, D.C., 1959.

Wang, Y., Ed., *CRC Handbook of Radioactive Nuclides*, Chemical Rubber Co., Boca Raton, Fla., 1969.

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Table 1
RADIONUCLIDES

Atomic number	Radionuclide	Physical half-life	Major radiations
1	Hydrogen-3 (^{3}H)	12.26 years	β^-
4	Beryllium-7 (^{7}Be)	53.37 days	γ
6	Carbon-14 (^{14}C)	5730 years	β^-
9	Fluorine-18 (^{18}F)	109.7 min	β^+,γ
11	Sodium-22 (^{22}Na)	2.602 years	β^+,γ
	Sodium-24 (^{24}Na)	15.0 hr	β^-,γ
14	Silicon-31 (^{31}Si)	2.62 hr	β^-,γ
15	Phosphorus-32 (^{32}P)	14.3 days	β^-
16	Sulfur-35 (^{35}S)	88 days	β^-
17	Chlorine-36 (^{36}Cl)	3.1×10^5 years	β^-,γ
	Chlorine-38 (^{38}Cl)	37.3 min	β^-,γ
18	Argon-37 (^{37}Ar)	35.1 days	γ
	Argon-41 (^{41}Ar)	1.83 hr	β^-,γ
19	Potassium-40 (^{40}K)	1.28×10^9 years	β^-,β^+,γ
	Potassium-42 (^{42}K)	12.4 hr	$\beta^-\gamma$
20	Calcium-45 (^{45}Ca)	165 days	β^-
	Calcium-47 (^{47}Ca)	4.53 days	β^-,γ
21	Scandium-46 (^{46}Sc)	83.80 days	β^-,γ
	Scandium-47 (^{47}Sc)	3.43 days	β^-,γ
	Scandium-48 (^{48}Sc)	1.83 days	β^-,γ
23	Vanadium-48 (^{48}V)	16.0 days	β^+,γ
24	Chromium-51 (^{51}Cr)	27.8 days	γ,e^-
25	Manganese-52 (^{52}Mn)	5.7 days	β^+,γ
	Manganese-54 (^{54}Mn)	303 days	γ,e^-
	Manganese-56 (^{56}Mn)	2.576 hr	β^-,γ
26	Iron-55 (^{55}Fe)	2.6 years	γ
	Iron-59 (^{59}Fe)	45.1 days	β^-,γ
27	Cobalt-57 (^{57}Co)	270 days	γ,e^-
	Cobalt-58m (^{58m}Co)	9.0 hr	γe^-
	Cobalt-58 (^{58}Co)	71.3 days	β^+,γ
	Cobalt-60 (^{60}Co)	5.26 years	β^-,γ
28	Nickel-59 (^{59}Ni)	8×10^4 years	γ
	Nicle-63 (^{63}Ni)	92 years	β^-
	Nickel-65 (^{65}Ni)	2.521 hr	β^-,γ
29	Copper-64 (^{64}Cu)	12.9 hr	$\beta^-,\beta^+,e^-,\gamma$
30	Zinc-65 (^{65}Zn)	243.6 days	β^+,e^-,γ
	Zinc-69m (^{69m}Zn)	13.9 hr	γ,e^-
	Zinc-69 (^{69}Zn)	58 min	β^-
31	Gallium-72 (^{72}Ga)	14.10 hr	β^-,γ
32	Germanium-71 (^{71}Ge)	11.4 days	γ
33	Arsenic-73 (^{73}As)	80.3 days	γ,e^-
	Arsenic-74 (^{74}As)	17.9 days	β^-,β^+,γ
	Arsenic-76 (^{76}As)	26.5 hr	β^-,γ
	Arsenic-77 (^{77}As)	38.83 hr	β^-,γ
34	Selenium-75 (^{75}Se)	120.4 days	γ,e^-
35	Bromine-82 (^{82}Br)	35.5 hr	β^-,γ
36	Krypton-85m (^{85m}Kr)	4.4 hr	β^-,e^-,γ
	Krypton-85 (^{85}Kr)	10.76 years	β^-,γ
	Krypton-87 (^{87}Kr)	76 min	β^-,γ
37	Rubidium-86 (^{86}Rb)	18.66 days	β^-,γ
	Rubidium-87 (^{87}Rb)	5×10^{11}years	β^-
38	Strontium-85m (^{85m}Sr)	70 min	γ,e^-
	Strontium-85 (^{85}Sr)	64 days	γ,e^-
	Strontium-89 (^{89}Sr)	52 days	β^-,γ
	Strontium-90 (^{90}Sr)	28.1 years	β^-

Table 1 (continued)
RADIONUCLIDES

Atomic number	Radionuclide	Physical half-life	Major radiations
	Strontium-91 (^{91}Sr)	9.67 hr	β^-,γ
	Strontium-92 (^{92}Sr)	2.71 hr	β^-,γ
39	Yttrium-90 (^{90}Y)	64 hr	β^-
	Yttrium-91m (^{91m}Y)	50 min	γ,e$^-$
	Yttrium-91 (^{91}Y)	58.8 days	β^-,γ
	Yttrium-92 (^{92}Y)	3.53 hr	β^-,γ
	Yttrium-93 (^{93}Y)	10.2 hr	β^-,γ
40	Zirconium-93 (^{93}Zr)	1.5 × 10^6 years	β^-
	Zirconium-95 (^{95}Zr)	65 days	β^-,γ
	Zirconium-97 (^{97}Zr)	17 hr	β^-,γ
41	Niobium-92m (^{92m}Nb)	10.14 days	γ
	Niobium-93m (^{93m}Nb)	13.6 years	γ,e$^-$
	Niobium-95 (^{95}Nb)	35.15 days	β^-,γ
	Niobium-97 (^{97}Nb)	72 min	β^-,γ
42	Molybeenum-99 (^{99}Mo)	66.69 hr	β^-,γ
43	Technetium-96m (^{96m}Tc)	52 min	γ,e$^-$
	Technetium-96 (^{96}Tc)	4.35 days	γ,e$^-$
	Technetium-97m (^{97m}Tc)	90 days	γ,e$^-$
	Technetium-97 (^{97}Tc)	2.6 × 10^6 years	γ
	Technetium-99m (^{99m}Tc)	6.0 hr	γ,e$^-$
	Technetium-99 (^{99}Tc)	2.12 × 10^5 years	β^-
44	Ruthenium-97 (^{97}Ru)	2.9 days	γ,e$^-$
	Ruthenium-103 (^{103}Ru)	39.6 days	β^-,γ
	Ruthenium-105 (^{105}Ru)	4.44 hr	β^-,γ
	Ruthenium-106 (^{106}Ru)	367 days	β^-
45	Rhodium-103m (^{103m}Rh)	57.5 min	γ,e$^-$
	Rhodium-105 (^{105}Rh)	35.9 hr	β^-,γ
	Rhodium-106 (^{106}Rh)	30 sec	β^-,γ
	Rhodium-106 (^{106}Rh)	130 min	β^-,γ
46	Palladium-103 (^{103}Pd)	17 days	γ
	Palladium-109 (^{109}Pd)	13.47 hr	β^-,e$^-$,γ
47	Silver-105 (^{105}Ag)	40 days	γ,e$^-$
	Silver-110m (^{110m}Ag)	253 days	β^-,e$^-$,γ
	Silver-111 (^{111}Ag)	7.5 days	β^-,γ
48	Cadmium-109 (^{109}Cd)	450 days	γ,e$^-$
	Cadmium-115m (^{115m}Cd)	43 days	β^-,γ
	Cadmium-115 (^{115}Cd)	53.3 hr	β^-,γ
49	Indium-113m (^{113m}In)	100 min	γ,e$^-$
	Indium-114m (^{114m}In)	50.0 days	γ,e$^-$
	Indium-115m (^{115m}In)	4.50 hr	β^-,e$^-$,γ
	Indium-115 (^{115}In)	6 × 10^{14} years	β^-
	Indium-118 (^{118}In)	5 sec	β^-,γ
	Indium-118 (^{118}In)	4.4 min	β^-,γ
50	Tin-113 (^{113}Sn)	115 days	γ
	Tin-125 (^{125}Sn)	9.4 days	β^-,γ
51	Antimony-122 (^{122}Sb)	2.8 days	β^-,β^+,γ
	Antimony-124 (^{124}Sb)	60.3 days	β^-,γ
	Antimony-125 (^{125}Sb)	2.7 years	β^-,e$^-$,γ
52	Tellurium-125m (^{125m}Te)	58 days	e$^-$,γ
	Tellurium-127m (^{127m}Te)	109 days	γ,e$^-$,β^-
	Tellurium-127 (^{127}Te)	9.4 hr	β^-,γ
	Tellurium-129m (^{129m}Te)	34 days	β^-,e$^-$,γ
	Tellurium-129 (^{129}Te)	69 min	β^-,e$^-$,γ
	Tellurium-131m (^{131m}Te)	30 hr	β^-,e$^-$,γ
	Tellurium-132 (^{132}Te)	78 hr	β^-,e$^-$,γ

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Table 1 (continued)
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